THE ATOM
AND ITS ENERGY

by

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I DEDICATE THIS BOOK
TO MY DEAR WIFE
MONA
NOT KNOWING ANY PERSON
WHOM I LOVE SO WELL
NOR ANY
TO WHOM
I AM MORE INDEBTED

PREFACE

THE interest excited by the atomic bomb, and by the prospect of the application of nuclear energy to peaceful ends, is sufficient excuse for the production of a book which sets out to explain to the reader not trained in the physical sciences the broad principles involved and the general results obtained. There are, it is true, already excellent books in the field, but those which I have seen deal almost entirely with the recent and sensational developments which have, very naturally, impressed the imagination and awakened the fears of all thinking men and women. What I endeavour to do here is so to discuss the general elements of the atomic theory, and the observations on which it is based, that these developments shall appear to be the inevitable outcome of an ordered body of investigation which has led us to a more and more detailed knowledge of the atom and its structure, culminating in our penetration into the nucleus, on which the future of the world is balanced.

The earlier part of this little volume embodies much of the matter contained in a booklet entitled *The Atom*, which, originally published in 1927 by Messrs. Benn, was last issued in 1936 by Messrs. Thomas Nelson as a volume, now out of print, of the Nelson Classics. I am very grateful to Messrs. Nelson for allowing me to use it. This matter has been extensively rewritten and the latter part of this book, in particular Chapters VII and VIII, is completely new.

The sources of those of the illustrations which are borrowed are acknowledged when they are used. I am very grateful to the Royal Society, the Physical Society, Sir Lawrence Bragg, M. Leprince-Ringuet, Messrs. Arnold, The Macmillan Co., Monsanto Chemicals Ltd. and the United Nations Department of Public Information, New York. The paper *Chemical Engineering* (McGraw-Hill Publishing Co.) was kind enough to let me have the picture of the diffusion plant at Clinton. My best thanks are due to Dr. Donald Cooksey, of the Berkeley Radiation Laboratory, for photographs of the cyclotron and a most obliging letter. I need scarcely acknowledge my indebtedness to the Smyth Report, to which anyone who writes on nuclear energy must constantly refer. Mr. F. A. Drey was kind enough to find for me, at my request, the photograph from which Lucas van Leyden's picture is reproduced.

I offer my sincere thanks to Dr. John Cockroft, who read Chapter VIII and made certain valuable suggestions. I have also had the advantage of consultation with Professor H. S. W. Massey and with Dr. W. E. Duncanson on certain points. I am very grateful to Mr. R. E. Jennings for reading through the proofs. It is a pleasure to acknowledge that my assistant, Mr. L. Walden, G.M., rendered valuable help in the preparation of many of the illustrations.

E. N. DA C. ANDRADE.

Written at my small house
in St. John's Wood, April, 1947.

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The mind of man has perplexed itself with many hard questions. Is space infinite, and if so in what sense? Is the material world infinite in extent, and are all places within that extent equally full of matter? Do atoms exist, or is matter infinitely divisible?

JAMES CLERK MAXWELL, 1873

Wie sich Verdienst und Glück verketten,
Das fällt den Toren niemals ein;
Wenn sie den Stein der Weisen hätten,
Der Weise mangelte dem Stein.

GOETHE. *Faust II. Act* I

I

THE ATOMIC THEORY

> These observations have tacitly led to the conclusion which seems universally adopted, that all bodies of sensible magnitude, whether liquid or solid, are constituted of a vast number of extremely small particles, or atoms of matter.
>
> JOHN DALTON. *A New System of Chemical Philosophy.* 1808

FROM the time when serious thinking about ourselves and our surroundings began, the question has been asked as to what matter is made of. In particular, the following problem has been discussed: suppose we could take a piece of some substance, say copper, and magnify it indefinitely, should we see in the end that it was made up of particles with spaces between them, held together by certain attractive forces, or should we find that, no matter how much larger we made it appear, it was as continuous throughout as it appeared when unmagnified? To take a homely simile, would it appear like a bushel of peas, or like a jelly? Another way of asking this question is to demand whether, supposing our senses were fine enough and our instruments delicate enough, we could go on dividing up a piece of matter, say, copper, into smaller and smaller fragments indefinitely, or whether we should at last come to a fragment which could not be further divided, at any rate without its ceasing to be copper. On the bushel of peas theory, we should come to an end when we had isolated a single pea, while we could go on

chopping our little bit of jelly smaller and smaller without coming to a recognizable ultimate part.

The atomic theory is the bushel of peas theory. It assumes that all matter is ultimately made up of little grains, which are called atoms because they cannot be further divided. For the word "atom" is derived from the Greek and means "that which cannot be cut." Until within the last forty or fifty years it was believed that an atom could not be damaged in the slightest by any agency of nature or of the laboratory, but we know now that an atom has a structure which can be considerably modified by suitable agencies. We can remove with ease the outer component parts of the atom; or, in general terms, chip little bits off it. The exact meaning of this will be discussed later on in the book: it is not of importance for our present purpose. If, changing our metaphor, we call atoms the bricks out of which pieces of matter—of copper, quicksilver, carbon, and suchlike—are built, they are no less our ultimate bricks because we can, by certain methods, chip little pieces from them which are easily restored. We cannot cut them in half, and have two half-bricks with the same properties as the original bricks. It is true that we can to-day, by very special methods, divide certain kinds of atoms into two, but the two parts are something completely different from the original atom, which has lost its essence and properties. As far as ordinary chemistry is concerned, the atoms maintain their nature and individuality.

The question at once arises as to how many different kinds of atoms we must have. We are acquainted with hundreds of thousands of different kinds of substances: with different metals, different woods, different

stones; with the parts of living organisms, such as bones and flesh; with the enormous variety of different chemical substances which play so large a part in our life and industry, and, in contrast, with ill-defined messes, such as mud, and the products of the average cook. Are we to assume that to each substance corresponds a different atom: that the ultimate constituent of copper is a little atom of copper, the ultimate constituent of bone a little atom of bone, and the ultimate constituent of mud a little atom of mud? The last would clearly be absurd, for we know that mud is made by mixing various things; for instance, water, clay and the little particles of wood, stone, fibre and what not which we call dust, so that in any case it will be sufficient to discuss the ultimate parts of these things which are mixed. Suppose, then, we confine ourselves for the moment to definite chemical substances, such as copper and quicksilver, salt and sugar, water and alcohol, and inquire about their ultimate structures. Are they simply things, each with its own kind of atom, or can they be built up of other substances?

The answer, provided by the science of chemistry, is that certain substances are simple, and cannot by chemical means be built up of other substances, but that the vast majority of substances are compounds, which can be made in the laboratory—if not in the laboratory of flasks and test tubes, then in the wonderfully equipped laboratory which is constituted by living matter, animal and plant—from the simple substances. Thus the solids, copper, sulphur, carbon; the liquids, quicksilver and bromine; the gases, oxygen, nitrogen, and hydrogen, are examples of simple substances, which cannot be manufactured by making substances combine.

Such substances are called elements.[1] Some ninety chemical elements, in the sense just defined, are known. Familiar substances which are elements are the pure metals (as distinct from alloys), such as aluminium, iron, cobalt, nickel, zinc, platinum; the non-metallic solids, carbon, arsenic, iodine and phosphorus; and the liquids and gases just mentioned. Some of these elements occur much more commonly than others; thus the eight elements oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium make up nearly ninety-nine-hundredths by weight of the earth's crust, while the fifty least common elements, which include many useful metals, all together constitute only about one ten-thousandth of the earth's crust. It will come as a surprise to many that oxygen is the commonest element, not, of course, as a gas, but because it is combined in important proportions by weight in nearly all common substances. About 98 per cent. of igneous rock, for instance, is made up of silica, alumina, oxides of iron, magnesia, lime, soda, potash and water, each of which is a compound containing a high percentage of oxygen.

From these chemical elements all known substances are built up, just as from a few types of girders, beams, plates, and so on, the steel work of all structures, bridges of various sizes and shapes, towers, and suchlike can be made. Thus ordinary kitchen salt is a compound of the soft metal sodium and the gas chlorine, while sugar

[1] The use of the word element to denote the four supposedly, but not actually, simple substances earth, air, fire, and water, is a relic of an ancient Greek system, and has no place in modern science. It seems to have originated with Empedocles, a philosopher who flourished about 450 B.C. and who, like other philosophers of his era, occupied himself in building up schemes of nature from innate views as to the fitness of things.

is composed of carbon, oxygen and hydrogen. Marble is composed of calcium, carbon and oxygen; hydrogen peroxide, by which blondes are manufactured, of oxygen and hydrogen.

These substances will serve to illustrate a few of the facts of chemistry which we require for our discussion. In the first place we see that, when elements combine, the obvious properties of the compound have nothing to do with the properties of the elements from which it is made. Sodium is a soft substance, which can be cut with a knife, leaving a metallic surface which tarnishes at once in air; if thrown into water, it floats and decomposes the water so vigorously that, in certain circumstances, combustion and explosions may ensue. Chlorine is poisonous to breathe; in fact, it was the first gas to be used as poison gas in the Great War of 1914–18. Yet chlorine combines readily with sodium to form ordinary salt, which is wholesome, and dissolves in water without fuss. When marble is acted upon by acid, the carbon and part of the oxygen are given off, combined together to form the familiar gas carbon dioxide, used to aerate drinks. Carbon—or coke—and the two gases, hydrogen and oxygen, combined in due proportions, form sugar; combined in other proportions, they form starch. Oxygen and hydrogen combined in certain proportions form water; in other proportions, hydrogen peroxide.

We see, therefore, in the first place, that in a compound the properties of the combining substances are completely hidden; the substance resulting from a chemical reaction between different substances does not show a kind of average of their qualities, but has its own distinct individuality. The general reason

that in a compound the properties of the individual atoms do not appear is that the chemical properties of the atom are given by its outside parts, and in the compound the outside parts of the joined atoms are modified by the forces involved in the combination. In the second place, substances combine in perfectly definite proportions by weight to form a given substance; they are not mixed, like the ingredients of a pudding, where a little more or less of any one component may be allowed without altering the result, but put together in a precise way like a machine, where an exact number of component parts are required. In the third place, the same elements can combine in different proportions, forming quite different substances; but, when they do so, the proportions by weight of the elements in the different compounds bear quite simple relations to one another. For instance, in hydrogen peroxide there is exactly twice as much oxygen combined with a given weight of hydrogen as there is in water; the weight of oxygen combined with a given weight of lead in pure red lead (plumbers' red lead is usually a mixture of different chemical compounds) is four, as against six in the brown lead peroxide formed on the positive plate of an accumulator, and three in the oxide of lead known as litharge. These are particularly simple examples, but the laws just indicated are quite general.

Now on the atomic theory these laws, which have been discovered by experiment, are simply explained in the following way. Chemical compounds are formed by the atoms of different elements entering into combination with one another. For simplicity we will consider for the moment compounds, such as common

salt, water, or pure red lead, formed of two different elements only. In such compounds quite a few atoms —perhaps one, and seldom more than six—of an element combine with quite a few atoms of another element to form the smallest particle which can have the properties of the substance in question. Such a particle is called a molecule. For an elementary substance the atom and the molecule may be the same thing or they may not. For instance, a molecule of the gas neon, used in the discharge tubes made familiar by modern advertising signs, consists of a single atom of neon, for the atoms of this element do not combine with one another. With oxygen, however, the molecule consists of two exactly similar atoms joined together: we do not ordinarily, in the gaseous form of the element, find oxygen atoms singly, but always joined in pairs.

In the case of common salt, one atom of sodium combines with one atom of chlorine to form one molecule of salt, which is called in chemical language sodium chloride. In the case of carbon and oxygen, one atom of carbon combines with one atom of oxygen to form one molecule of carbon monoxide, which is a highly poisonous gas, formed by incomplete combustion: a once popular method of committing suicide with a charcoal brazier in a closed room depended upon the production of this gas, one part of which to a thousand parts of air is fatal. One atom of carbon can also combine with two atoms of oxygen to form carbon dioxide. The weight of oxygen combined with an ounce of carbon is exactly twice as great in carbon dioxide as in carbon monoxide. Iron forms two compounds with chlorine, in which the weights of

chlorine combined with a given weight of iron are as two to three: in the one compound one atom of iron is combined with the two atoms of chlorine; in the other compound, one atom of iron is combined with three atoms of chlorine. This conception of atoms combining explains why in true chemical compounds the proportions are always fixed, since every ultimate part, every molecule, of the compound consists of a perfectly definite small number of one kind of atom combined with a perfectly definite small number of another kind of atom. It also explains why, when the same two elements combine to form different compounds, the amount of the one element combined with a fixed amount of the other element, while different in the different compounds, is always a very small multiple of a fixed amount.

To make this quite clear, let us consider a business office which buys envelopes at a fixed rate, and franks all its letters with stamps of the same denomination, and let us further imagine that it has different departments for dealing with correspondence requiring different postage. Thus, one department sends out printed leaflets requiring a single stamp on the envelope; another department sends out cards, requiring two stamps; another department letters requiring three stamps; another department foreign letters requiring five stamps. In a given department the ratio of the amount spent on envelopes to the amount spent on stamps will always be the same; in another department it will be different, but the amount spent on stamps per envelope will be a simple multiple of that prevailing in the first department. Anybody investigating the books of the business, but never having

seen the actual dispatching of the mail, would come to the conclusion that the costs would be most simply explained by supposing that a single dispatch combined with a single stamp in one department, and with two, three, or more stamps in other departments. Substitute weights for costs, and compounds for departments, and we have the chemical facts.

The number of the atoms of each kind that make up a molecule is, however, only one of the features of chemical combination that are represented by the Atomic Theory. The arrangement and sizes of the atoms in all the simpler molecules, and in very many complicated ones, has also been worked out, and many features of chemical combination can only be understood on the basis of a knowledge of such molecular properties. A few models illustrating the structure of simple molecules are shown in Plate I. On the left at the top we have the molecule of water vapour, one oxygen atom combined with two hydrogen atoms arranged not in a line, but so that their centres form a triangle. Under this we have the molecule of hydrogen peroxide, with two oxygens and two hydrogens, and below this the ammonia molecule, with a central nitrogen atom to which three hydrogen atoms are symmetrically attached. On the right at the top we have the benzene molecule, which is at the foundation of a great branch of organic chemistry, with its ring of six carbon atoms, to each of which a hydrogen atom is joined: below it is the molecule of acetic acid, the acid of vinegar, with one carbon carrying three hydrogen atoms, while joined to it is another carbon atom attached to two oxygen atoms, one of which carries a hydrogen atom. This combination of a carbon atom

with two oxygen atoms and a hydrogen atom forms a group which is characteristic of organic acids.

The importance of the atomic theory in chemistry is that it enables us to form a picture of what is going on when chemical combination takes place, and to anticipate what we must do to form a given molecule. It is not too much to say that without this conception of atoms which can combine with one another to form a molecule, and which can interchange places when molecules are brought together, we should have none of the synthetic dye-stuffs and other complex compounds that we possess to-day. By means of the atomic theory, we can write down exactly what quantities of substances are required to take part in a given reaction, and can foretell what steps must be taken when it is desired to form one compound from another. The atomic theory is to chemistry what the drawing office, bookkeeping and accountancy are to an engineering business. We might carry on somehow without it, but we should have no control of our knowledge, no systematic record of our achievements to which we could refer, no reasoned lines for planning future campaigns.

We now turn to the application of the atomic theory to certain general aspects of the nature of matter, and in particular to the nature of heat. Matter as we know it can exist in three forms, as a solid, a liquid, or a gas, and a given substance can appear under one or the other form, according to the temperature and pressure. Thus, to take the familiar example of water, it is a solid, ice, when very cold; a liquid, under ordinary conditions; and an invisible gas, steam, when very hot, the temperature at which it turns into steam depending

on the pressure, as every engineer knows. We say that steam is an invisible gas, for what can be seen, and is ordinarily called steam, is minute drops of hot water, formed by the steam condensing in the cold air: close to the spout of a kettle there is a space where the issuing steam is too hot to condense, and so nothing can be seen. A somewhat less familiar example of the three states is the gas, carbon dioxide, used for making aerated drinks, which has already been mentioned. This is sold in steel cylinders, in which it exists under great pressure as a liquid. When it is let out slowly, with the tap end of the cylinder uppermost, it issues as an invisible gas, but if the cylinder be reversed and the liquid allowed to issue rapidly, intense cold is produced, and a snow-like substance is formed, which may be caught in a cloth wrapped round the nozzle. It is carbon dioxide in solid form. This solid, which is extremely cold, can to-day be purchased in blocks, under various trade names, for refrigerating purposes.

All substances which exist normally as gases, including the air we breathe, can nowadays be reduced to liquid and to solid form; liquid air can, in fact, be bought commercially, by the gallon. The last gas to be subdued was helium, which was not reduced to solid form until 1926. Whether a substance exists as a solid, a liquid, or a gas, does not, in fact, depend upon the nature of the substance, but upon the conditions. If the normal temperature of the world were that of a hot oven, we should (providing we could exist) speak of water substance as a gas, which could be liquefied and solidified by special means, and similarly, we should regard the metal tin as a liquid.

How are we to regard these different forms of matter

on the atomic theory? We must first say a word as to the nature of heat. Every body is made up of atoms, bound together in little clusters or molecules if the body is a compound, and not an element. These atoms or molecules are in ceaseless agitation, and so possess energy of motion.[1] This invisible, or internal energy, due not to the motion of the body as a whole, but to a dashing hither and thither of particles much too minute to be seen even with a microscope, is what we know as heat. The molecular motion is taking place in bodies at ordinary temperatures, but when we heat a body it becomes more violent, when we cool a body it becomes less marked. In a heat engine of any kind, we convert some of the irregular, invisible molecular motion into a regular visible motion of the piston or other moving part of the machine. From this view of heat we see at once a very important fact—namely, that there must be a limit of coldness, or an absolute zero of temperature below which we cannot go. For when a body is cold enough for all molecular motion to cease we cannot go to any lower temperature; molecules cannot be any less lively than still. It can be calculated that this so-called absolute zero of temperature is 273° C. below the melting-point of ice, and temperatures within a very small fraction of one degree of this limit have actually been attained in the laboratory. On the other hand, there is no limit of high temperature, for however energetically the molecules—or atoms, after the molecules have come

[1] In the case of an element where the atoms do not combine in pairs or greater numbers—an element like neon, as distinct from an element like oxygen—the atom is the unit that gives the properties characterizing the substance. In such a case the atom is also the molecule of the substance. We call such substances monomolecular: neon is a monomolecular gas.

to pieces—may be dashing about they can always go faster. It can be estimated that the temperature in the interior of certain stars is to be measured in millions of degrees, but it is inconceivable that anywhere there can exist a temperature lower than 273° C. below zero.

Now in matter we have a conflict between two influences. In the first place, the molecules exert forces on one another, forces both of attraction and repulsion. The forces of repulsion, however, die off very rapidly as we proceed outwards from the molecule, much more rapidly than do the attractive forces. The consequence is that at some distance the attractive forces prevail, and, if only the forces of attraction and repulsion had to be considered, the molecules would move together until they settled down, in solid form, at such distances from one another that the attractive and repulsive forces balanced: if the molecules were pushed together the repulsive forces would predominate, and if they were pulled apart the attractive forces would prevail. Things would be much the same as if we were dealing with rubber balls attracting one another by some special virtue. They would move together, touch and squeeze up a little until the elastic force of repulsion just balanced the mysterious attraction.

Against the attractive force, however, we have the movement of the molecules which constitutes heat: every one of them is in ceaseless agitation. The higher the temperature, the more violent the motion of the molecules. This motion tends to keep the molecules from settling down, and in this sense acts in the opposite way to the attractive forces. Whether a body exists in

the solid, liquid, or gaseous state depends upon the relative importance of the two effects.

In a solid the attractions prevail. The molecules occupy more or less fixed positions, depending upon the forces exerted by the other molecules, and their heat motion consists of a vibration or trembling of the molecule, which never takes it far from its fixed abode. In a liquid the attractions and the heat motions are more evenly balanced, so that, while the attractions play a considerable part, yet any molecule can work its way through the other molecules. It makes frequent collisions with them, but can slowly move by itself to a distant spot, or, if we care to stir the liquid, we can move some large groups of molecules further away from others. In a gas at ordinary pressure, the molecules are sparsely scattered, the attractions are relatively unimportant, and the molecules move in straight lines over distances which are large compared to the size of a molecule, and act on one another mainly by collisions. The pressure which a gas exerts is merely the effect of a bombardment on the side of the containing vessel by millions of millions of tiny molecular projectiles, which bounce off again. In a solid and a liquid the molecules are comparatively close, and the substance can only be compressed with difficulty: in a gas the molecules are separated by long distances, and the substance can be compressed easily. In air at ordinary temperatures the average distance between the molecules is about ten times the diameter of a molecule, and the average distance through which a molecule moves among its fellows without a collision is nearly three hundred times its diameter.

When we heat a substance we increase the energy of

the heat motion of the molecules, by communicating to them some of the energy of motion of the molecules of the heating body—flame or what not. Hence, although in the beginning the attractive forces between the molecules may be the predominating influence, as the temperature rises the heat agitation eventually becomes sufficient for the molecules to shake themselves loose from their moorings, as it were, and go cruising through the compact fleet which they constitute. The solid becomes a liquid. At a still higher temperature, the motion becomes so violent that the molecules fly off altogether from one another, and go shooting about with high velocity, the attraction only being appreciable when two molecules happen to collide, and then being insufficient to hold them together. This is the gaseous state.

We can form a rough human picture of what is going on in the following way. In a solid, the molecules can be pictured as a crowd of men all doing physical exercises—"the daily dozen"—without moving from the spot where they stand. They are moving their bodies to and fro or up and down: they may be swinging their arms at the same time. If they have taken up their positions at random, we have a so-called amorphous or non-crystalline solid, such as glass or glue: if they are neatly drawn up in rows by a drill instructor, we have a crystalline substance, such as quartz or rock-salt or washing soda. In a liquid the molecules can be pictured as a swarm of men gathered together in a hall at a crowded reception; they are tightly wedged, but each one works his way through the others, with many a push and apology, and we cannot expect the same two

men to be near each other all through the evening. (If we want two kinds of atoms, we may take men and women; if dancing starts we have chemical combination, two atoms combining to form a molecule.) For a gas we have to think of a large open space on which men are walking without looking where they are going; each man continues in a straight line until he bumps into some one else, when he abruptly starts off again in a different direction. In each case, the hotter the substance the more rapid the motion. If a cinematograph picture could be taken of the molecules of the air in a room all we should have to do to represent the air in an oven would be to run the film more quickly.

We have now obtained some idea of the outlines of modern atomic theory. A piece of copper wire appears to be continuous and inert only because of the minuteness of the atoms, just as a large and animated crowd may appear to an observer high in an aeroplane merely as a tranquil brown patch. When chemical combination takes place, what really happens is a regrouping of atoms according to certain definite laws, just as, from a mixture of people, families will segregate. We have now to inquire as to how the existence, size, and number of the atoms have been definitely established.

II

THE SIZE AND THE NUMBER OF ATOMS

Quoique les Corps ne puissent être divisés jusqu'à l'infini, ils peuvent pourtant l'être jusqu'à une petitesse fort étonnante. Nous allons le faire voir par quelques exemples.[1]

VAN MUSSCHENBROEK. *Essai de Physique.* 1739

It is as easy to count atomies as to resolve the propositions of a lover.

SHAKESPEARE. *As You Like It.* III. 2

We have discussed how the theory that all bodies consist of atoms can be used to explain the broad facts of chemical combination and of the constitution of bodies. The question now arises as to whether we cannot find out something more precise about atoms: how big they are, and how close they are in different bodies—that is, how many of them there are in a piece of matter of a given size. Science is a detective story, and Nature provides us with plenty of clues, if we know how to look for them. What are the clues to the size of the atom, and how can we use them to deduce the results we require? The clues discussed in the last chapter were very general, and it might be supposed that we had placed a wrong interpretation on them. If we can check them by more detailed evidence, we

[1] "Although bodies cannot be divided up infinitely, yet they can be so divided to an astonishingly small size. We will make this clear by some examples."

shall feel more confident that we have not been on the wrong track.

As in a detective story, the results of the investigation are often given first, to arouse the reader's interest, and the methods by which they were reached described later, we will at once state the facts of which every man of science is now convinced. Atoms are not all of the same size, but they are all of the same kind of size. If some one who had no idea of what birds or their eggs were like were to ask us the size of a bird's egg, we should not waste time going into details of the different eggs, but should answer: they are an inch, or a few inches or so, across. In the same way, we can say that atoms are a hundred-millionth of an inch or so across, the smallest atom, the hydrogen atom, having a diameter of about half a hundred-millionth of an inch. About a hundred thousand atoms placed side by side make up the thickness of a cigarette paper. This may not sound so incredibly small at first, but it means that in a little cube cut from a cigarette paper, the width and breadth and height of which are all equal to the thickness of the paper (that is, in a tiny grain of dust) there are some thousand million million atoms. This assumes that in a solid the atoms are touching, or nearly touching, which we know to be true.

Many striking ways can be devised for expressing the great number of atoms in a tiny grain of matter. Thus, if a staff of a thousand men were told off to count the atoms in a single one of the little bubbles of gas which collect on the side of a glass of soda-water, and if each man could count three hundred atoms a minute, and counted twelve hours a day all the year round, the job would take a million years, or, putting the population

of the world at three thousand millions, and supposing everybody to count at the rate specified, it would take four months. Or again, imagine a fine human hair magnified until it filled a street, the sides of the hair touching the houses on either side. Then a blood corpuscle, which might be adhering to the hair if it had been plucked out, would be about the size of the top of a large round table—that is, a disc of some six or seven feet across—but an atom would only be a speck of dust a thousandth of an inch across.

This suggests that the most direct way of measuring the size of the atom would be to use a very powerful microscope, and magnify up a tiny speck of matter until we could see the atoms of which it was composed.[1] This, however, is impossible. We cannot profitably magnify more than a few thousand diameters; greater magnification can be easily produced, but any increase above the figure stated leads to no further detail. This is a consequence of the fact that light itself is a wave motion, and so has a certain structure, with the result that we cannot hope to see the size or shape of anything which is smaller than a certain size, even if it kept still —and we know that atoms do not keep still, except at absolute zero.

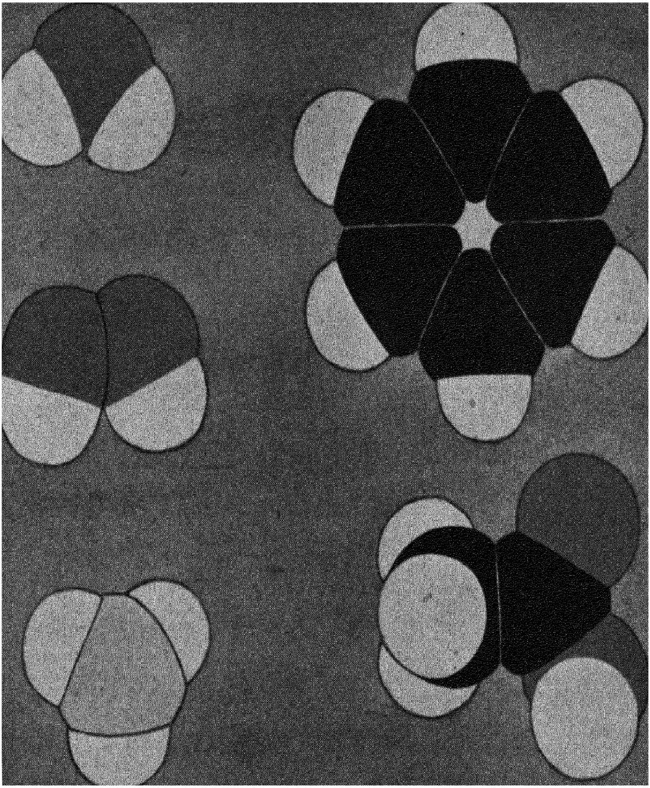
We can illustrate this fact by a simple analogy. When photographs are reproduced in newspapers, a so-called process screen is used, the result of which is that the picture is broken up into a mass of black and white dots. Now suppose we wished to see the individual threads in the coat of a man in the newspaper

[1] As early as 1680 the famous microscopist Leeuwenhoek wrote: "That which put me upon this speculation was, the Query put to me, Whether I could, by my microscope, discern the Particles of which Water doth consist?"

picture. We could magnify up the picture with a magnifying-glass or a microscope until a thing the size of a thread ought to be visible, but it would not help us. The structure of the screen is too coarse, and we should merely see a very large dot. Even if we had the original photograph, the same kind of limit would be set by the grain of the plate. The wave structure of light produces a similar kind of effect, preventing us from seeing details finer than a certain size, which is about the wave-length of the light in question. Not only can we not see atoms by using an ordinary microscope, but we can never hope to do so, however perfect the instrument be made. That, however, does not mean that we cannot see certain effects due to them, certain clues from which the behaviour and size of the atoms can be deduced, just as the skilled detective can deduce all the facts of a murder without ever hoping to be, or to find, an eye-witness.

First of all, let us consider some very simple experiments which show us that the atom must be very small. If a tiny droplet of oil, whose size can be measured, be placed on the surface of perfectly clean water, it spreads out, and covers a very large surface. From the size of the surface covered the thickness of the film can be simply calculated, and, since the film must be at least one atom thick, this thickness gives us what is called an upper limit for the size of the atom, that is, a size which the diameter of the atom cannot possibly exceed, although it may, of course, be much smaller. In the most delicate experiments which have been carried out with oil films, it is difficult to see the boundary of the film, and ingenious methods have been used to determine it. One method which has been used is to

PLATE I



Models illustrating the way in which molecules are built up of atoms.

As arranged above, the models represent:

water, H_2O

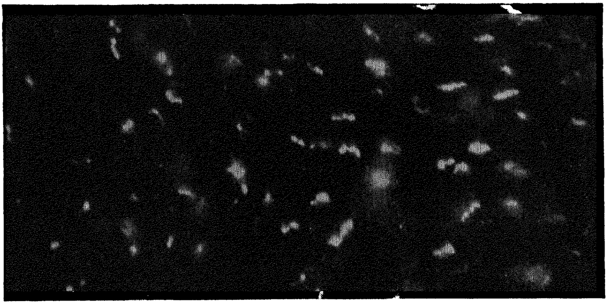
hydrogen peroxide, H_2O_2

ammonia, NH_3

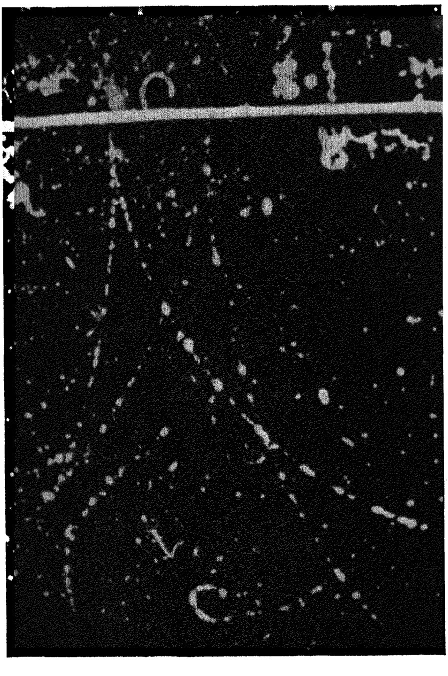
benzene, C_6H_6

acetic acid, $CH_3.COOH$

PLATE II



(*a*) The Brownian movement, due to molecular agitation, shown by smoke particles in air. Magnified 40 times. *Photograph by E. N. da C. Andrade and R. C. Parker.*



(*b*) Two pairs of positive and negative electrons.

The horizontal white line near the top is a lead plate: from each of two points in it proceed a positive and negative electron, the path of one curving in one direction, and that of the other in the opposite direction.

Photograph by W. A. Fowler and C. C. Lauritsen.

put tiny chips of camphor on the water: on clean water the chips dart about, as any one can confirm for himself, but on a grease film they do not. A still more sensitive method is to sprinkle very fine talc powder on the water, and then blow it. On the clean water the talc moves easily, but its movement is stopped at the edge of the oil film. In other experiments a spreading oil film can be made to push back the talc particles, thus demonstrating the boundary of the film. In these ways it has been shown that continuous oil-films, not thicker than half a ten-millionth of an inch, can be obtained, so that atoms must be smaller than this. This is a very simple clue, which tells us not to expect anything large.

More precise information is based upon the atomic theory of gases, which is generally called the kinetic, or the dynamic, theory, since it accounts for the properties of gases by the motion of the atoms. For general purposes we may think of the atoms as little balls dashing hither and thither, and colliding with one another. Now liquids and gases have a property which is called viscosity, by virtue of which they require a certain force to keep them in motion: if it were not for this viscosity (or internal friction, as it is sometimes called) a stirred liquid would go on moving for ever after the stirring had stopped. Roughly speaking, the more difficult it is to maintain a liquid in motion, the more viscous it is: thus treacle is very viscous indeed; glycerine is also very viscous; water has a much smaller viscosity, and ether, the anæsthetic, a lower viscosity still.

Gases are also viscous, though, of course, very much less so than liquids: for instance, it requires a pressure

to make a gas go through a small pipe, a pendulum swinging in air without any machinery to keep it going comes to rest sooner than it would do in a very high vacuum, and if air in a closed room be set in motion by a fan it soon settles down. It can be shown mathematically that this viscosity of a gas depends upon the average distance through which a gas molecule goes without making a collision, and this will clearly depend upon the number and the cross-section of the molecules —that is, upon the target which they offer to the other moving molecules. Thus, if there were a hundred large balloons drifting about irregularly in a certain space, a given balloon would go a less distance without a collision than a toy balloon would do among ninety-nine other toy balloons in the same space. From viscosity measurements it can be shown that the total cross-section of all the molecules (that is, the cross-section of one molecule multiplied by the number of molecules) in a cubic inch of ice-cold air at ordinary pressure is about thirty square yards, or they would serve to make a mosaic flooring one molecule thick for an ordinary living-room. This does not tell us, however, how big the molecules are, because we do not know how many there are: there might be a million, each thirty millionths of a square yard in area, or ten million each three millionths of a square yard in area, and so on. But now suppose we squeeze the gas as much as possible, cooling it if necessary, until we liquefy it. We then believe that the molecules are nearly touching. If we measure the space into which we have squeezed the original cubic inch of gas, we then know how much space the original number of molecules takes up, and this gives us another bit of

information about the number and the size. From this and the total cross-section of all the molecules, it is easy to calculate both the number of molecules and their size.[1] Or instead of acutally liquefying the gas, we may merely observe how it behaves when it is so compressed that the molecules come very close together: from the anomalous effects which appear, the mathematician can find out what is about the total volume of the molecules.

This method of considering the properties of gases is only one way of finding the size of molecules. Why we feel so certain that we are approximately right is that there are several other ways of finding the same thing, and they all give about the same result. When the detective finds that the footprints point to one particular man, he may be fairly confident, but if he finds the fingerprints, and the weapon, and the motor car, and the button, and the other stock clues all pointing to the same man, he may well feel absolutely certain. Now a very different way of estimating molecular size is to use X-rays to investigate the structure of crystals, in which the molecules are arranged side by side, and very nearly touching. The X-rays are reflected at certain angles for crystals, and a close chain of reasoning, which we need not follow here, enables us to deduce the spacing of the molecules from the angle at which reflection takes place. The optical properties of gases can also be made to tell us something

[1] To make the nature of the problem clear, we may throw it into the following very simple form: we know that a number of cubical wooden blocks, when laid out one block thick, just cover a floor of seventy-two square yards, while when built up together they will just make a large block one yard cube: how many blocks are there, and how big is a single block? The answer will be found to be 373,248 blocks, each one half-inch cube.

about the size of the molecules. All these methods of approach, and still others, give the same sort of size.

It can be shown, from considerations of the densities of gases and certain chemical facts, that there are the same number of molecules in a fixed volume (say, one cubic inch) of a gas at standard pressure, no matter what the nature of the gas may be. The different densities of different gases at a standard pressure is a consequence of difference of weight of molecules, not of difference in number. If we know this number of molecules in a given volume of gas, and also the weight of the gas, which can be found by the use of the balance, then we should be able to find straight off the weight of the single molecule of each kind of gas. We have already spoken of one way in which this number can be found. Of recent years, however, some very striking experiments have been made, which not only give us another way of finding this number, but also prove the existence of the motion of the molecules which we have assumed to be the essence of heat. We will close this chapter by discussing these experiments, for carrying out which Professor Perrin received the Nobel Prize for 1925.

The observation from which the experiments really originate was made as long ago as 1827 by the English botanist Brown. He observed that minute solid particles, which happened to be present in a plant liquid which he was examining with the microscope, were in ceaseless motion, quivering hither and thither in irregular zigzag courses. The smaller the particles, the more lively was the motion. This discovery attracted little attention, and for many years was regarded as a trivial phenomenon. Towards the end

of last century, however, the true nature of the motion, which is called the Brownian movement, began to be realized. It was clearly shown that the motion of each little particle was independent of that of its neighbours, unlike the motion of the motes in a sunbeam, which move together in flocks with the currents of air. It was further established that it had nothing to do with the light falling on the liquid. We are, in fact, looking at very small, but microscopically visible, particles being jostled by the very much smaller, microscopically invisible, molecules.

Smoke particles in air show the movement just as do particles in a liquid. The smoke must be enclosed in a small vessel and stringent precautions taken to prevent air currents if the true Brownian movement is to be observed. Plate II, *a*, is a photograph of smoke particles taken under such conditions, with special illumination and an exposure of 10 seconds. The irregular motion of the particles and their abrupt changes of direction, which differ in neighbouring particles, can be clearly seen.

Imagine a man in an aeroplane looking down on to the sea from such a height that he cannot see the waves, and so does not know if the surface is quite calm and still, or rough and agitated. Now suppose his eye falls on a large ship, which he can plainly see, riding with engines stopped. If it is quite calm, the ship will be at rest; if, however, it is rough, the ship will be rolling and pitching, and this motion he will be able to see. It will tell him of the existence of the waves, although they are very small compared to the ship, and he cannot see them directly. In the same way the tossing in all directions of the minute particles immersed in the

liquid tells us of the motion of the molecules, although we can never hope to see them directly.

In science, however, before we can be sure of anything, we have not only to get a general explanation, but to make measurements and see if the size of the effects which we are explaining comes out right, so as to agree with the calculations based on the theory. Now it can be shown mathematically that if we have a number of very small particles in a liquid, which are kept in motion by large numbers of molecules banging against them, the particles will not all sink to the bottom, as heavier particles do, but will remain suspended. There will, however, be more of them near the bottom than there are higher up, just as the atmosphere is denser near the ground than higher up. The distribution of the particles is, in fact, due to a conflict between gravity and the temperature agitation of the molecules. If the particles are large, like grains of sand, gravity wins completely and they all settle on the bottom. If the particles are as small as molecules—are, in fact, molecules—the temperature agitation wins, and they are practically uniformly distributed. If they are microscopic particles there is a kind of compromise, and the particles do not settle completely: the smaller the particles the less the settlement.

By measuring with the help of a microscope the number of particles at different heights in a liquid, the number of molecules in a given volume of gas can be deduced. This sounds improbable, but it is so: the connecting link between the two facts is the consideration of the bombardment of the microscopic particles by water molecules in the one case, of the bombardment of a water molecule by other water molecules in the other

case. It was Einstein who clarified the whole theory of the Brownian motion.

If a little paint-water be made up with the water-colour paint gamboge, and a drop of this water be diluted until it is just feebly coloured, and then viewed through the microscope, it will be seen to be full of little spherical particles of the resinous gamboge. It was with a drop of such water that Perrin did his famous experiments, or rather with a layer or film of such water, less than a hundredth of an inch thick. With a powerful microscope he counted the number of little spheres at different heights, and by various methods he found the size and weight of the little spheres of gamboge. Calculating from his results, he came to the conclusion that in 1 cubic centimetre (a little less than one-sixteenth of a cubic inch) of any gas at atmospheric pressure, there are about twenty-seven million million million molecules. It follows, for example, that the weight of a molecule of oxygen, consisting of two atoms of oxygen stuck together, is about two billion-billionths of an ounce. Even if a molecule were a million million times as heavy as it is, we could not weigh it by our most refined balances. It is astonishing to think, however, that the molecule was virtually weighed by looking through a microscope at a very small drop of what appeared to be only slightly dirty water.

The Brownian movement of the particles is a true case of perpetual motion. When we come down to so small a scale as this, all our ordinary laws have to be revised. In ordinary life we do not see a brick suddenly move upwards by itself, but a minute particle in a liquid all at one temperature, without currents in it,

may, if struck by rather more molecules from underneath than from above, suddenly move upwards. So, as a matter of fact, may a brick; but if we calculate the chances that enough extra molecules may hit the brick from underneath to raise it, we find that we should have to wait several million million years for it to give a good jump. Even the laziest workman might hesitate to sit on a scaffold on the off-chance that the brick might jump up to him. A microbe workman in a liquid might, however, reasonably sit on his scaffold and wait for the Brownian movement to throw up his microscopic bricks, supposing he could build a house. The energy, of course, comes from the energy of motion of the liquid. But when we work on a large scale there is no possibility of using the energy of a liquid in this way, unless it is hotter than its surroundings, as it is in the boiler of a steam-engine. If the possibility existed, we might use up some of the energy of motion of the molecules in any pond, leaving the pond a little colder than when we found it. The denial that we can convert the heat of a body into work by cooling it below the temperature of its surroundings constitutes what is called the second law of thermodynamics, but this law applies to matter in bulk, and not to single molecules, or to particles consisting of comparatively few molecules.

Another way of expressing this is to say that in the science of heat we deal with probabilities. A minute particle in a fluid is in ceaseless motion because the chance of it receiving, from the hail of molecular blows from all sides, an unbalanced push, sufficient to move it appreciably, is fairly large. In the same way, if we toss a penny nine times the chance of getting at least

twice as many heads as tails is not too remote, roughly three to one against. With a large particle, a grain of sand or a small stone, however, the chance of an unbalanced push sufficient to move it appreciably is very remote indeed: it is not impossible, any more than it is impossible that if we toss a penny nine hundred times we shall get at least six hundred heads, but it is so unlikely that it comes to the same thing practically, if not philosophically.

It is impossible in the restricted space of this little book to make clear the exact reasoning by which the existence, size, mass, and number of the molecules have been demonstrated. It may, nevertheless, be hoped that enough has been said in this chapter to indicate to the reader that simple experiments may be made to yield remarkable results in the hands of imaginative and experienced workers. The whole of our theories of the atom rest upon the foundation of careful measurements of observed phenomena. The methods which have been mentioned are only a few selected for their simplicity from a large number which have been devised. The strength of the present position of the atomic theory is that markedly different methods all confirm the results which have been quoted.

III

THE ATOM OF ELECTRICITY

At first there were very few who believed in the existence of these bodies smaller than atoms. . . . I was not surprised at this, as I had myself come to this explanation of my experiments with great reluctance, and it was only after I was convinced that the experiments left no escape from it that I published my belief in the existence of bodies smaller than atoms.

J. J. THOMSON, referring to 1897, in *Recollections and Reflections*. 1936

A FORM of energy with which we are very familiar is that which we know as electricity. Nature occasionally gives us a striking display of electrical forces at work in the thunderstorm—occasionally, that is, at a given spot, for there is always an electrical disturbance going on in the atmosphere. It is, in fact, estimated that, when the whole earth is taken into account, there are about a hundred lightning flashes per second taking place all the time. These phenomena are caused by the movement of large charges of electricity from one place to another, under the influence of very high voltages.

If we turn from these irregular and uncontrolled displays to the well-governed behaviour of electricity in the service of man, we find that, in general, we can again reduce everything to the movement of charges of electricity. In the case of our electric lamp, or our electric motor, we have an electric current passing

through a wire, and an electric current is simply charges of electricity moving under a difference of electrical potential, just as the current of water in a river is a mass of water moving under the influence of a difference of level. In the case of our wireless waves, the disturbances which travel through space are started by large charges of electricity which are made to rush up and down the wires of the sending aerial. A charge of static electricity is generated when we rub a stick of sealing-wax or of glass on our sleeve and attract scraps of paper, and all the common effects of electricity with which we are familiar are due to nothing but such charges in motion. It is clearly, then, a matter of fundamental importance to know the nature of this electrical charge, and, in particular, whether it can be indefinitely divided and divided into charges as small as we please, or whether there is an atom of electricity just as there is an atom of matter.

Before we pass on it may be well to say a word about positive and negative electric charges. If we electrify two light suspended balls by giving them each part of the charge from a rubbed stick of sealing wax, then they repel one another. If we take two further balls and electrify them by giving them each part of the charge from a rubbed stick of glass they likewise repel one another. A ball charged from sealing-wax, however attracts a ball charged from glass. There is something essentially different in electricity generated by rubbing sealing-wax from that generated by rubbing glass: we say that these two kinds of electricity, which at one time was called resinous and vitreous electricity, are unlike, or of opposite signs. It is a fundamental fact that like charges repel one another,

while unlike charges attract. In 1778 Lichtenberg suggested for the glass, or vitreous, kind of electricity the term positive electricity, for the sealing-wax, or resinous, kind the term negative electricity, and these are the terms used to-day. It is, however, only by chance that the term "positive" fell to vitreous rather than to resinous electricity: there is nothing particularly positive about it.

The first suspicion that there might be an atom of electricity arose from the consideration of the passage of electricity through solutions of metallic salts, such as those which are used for electroplating. When the current is passed through such a liquid by means of two plates, called electrodes, immersed in it, it conveys a certain amount of the metal out of the solution on to one plate. It is found that if the same current be passed through solutions of chemical compounds of certain different metals for a fixed time, then the amount of metal deposited is proportional to the atomic weight—i.e. to the weight of the atom—of that metal. This could be explained if each metal atom, no matter what its nature, carried an atom of electric charge, as a horse carries a jockey. Certain other metals were deposited in lesser quantities than was, on this theory, to be expected from the amount of current passing, but then it was found that the amount moved could be accounted for on the assumption that every atom carried exactly two atoms of electric charge, or exactly three atoms of electric charge, but not a fraction of an atom of charge. This was a general argument for the atomic nature of electricity, but proof was to come from another direction.

We know that certain solids—namely, metals—will

allow an electric current to pass through them, and we have just been talking of certain liquids—namely, solutions of metallic salts—which will allow a current to pass through them. Will a gas allow a current to pass? As a result of the investigation of the passage of electricity through gases towards the end of the last century, the whole trend of physical science took a new turn.

When the air is at ordinary pressure, it requires very high voltages to force a current through an air gap of any length, and when the current at length passes it does so as a rending spark. But suppose we take a glass tube, inside which are two metal plates, joined to metal rods which pass out through the glass, so that we can connect them to a source of high potential, or high tension, as it is often called. The plate connected to the negative pole of our high tension battery or induction coil is called the cathode plate, or simply cathode: the plate connected to the positive pole is called the anode. Now, if we pump out the air from the tube, at a certain stage a luminous discharge passes from one electrode to the other, the colour of which depends upon the gas present. As the pressure is made lower and lower, the appearance of the discharge goes through a variety of beautiful changes until when the pressure in the tube is reduced to only a few hundred thousandths of ordinary atmospheric pressure, something new happens. The walls of the tubes opposite the cathode begin to glow with a greenish light, and, by having in the tube some body which casts a shadow, it is easy to show that the glow is due to something shot off by the cathode, which affects the glass where it strikes it. It is easy to limit the rays so that they form a narrow beam. The

investigation of these streams from the cathode, the so-called cathode rays, led to the discovery of the electron, or atom of electricity.

When a magnet is brought near, the beam of cathode rays is bent aside, as can be seen by the movement of the bright spot formed where it strikes the glass of the tube, or where it strikes a phosphorescent screen put inside the tube. The beam behaves just like a current of electricity, on which, as is well known, a magnet exerts a force, the direction of its movement being the same as if a negative charge of electricity were moving away from the cathode along the rays. It was soon proved in another way that the rays did carry a negative charge—namely, by catching them in a metal vessel and measuring the charge acquired by the vessel. The cathode rays can therefore be explained as a stream of electrified particles, and it might at first be supposed that they were atoms, each carrying a negative charge. When the man of science has to decide on such points, however, he always tries to measure the size of the effects in question, so that the problem arose of measuring the charge and the mass of the flying particles, and, incidentally, of proving that the rays did consist of flying particles.

The amount of the bending of the narrow beam of cathode rays produced by a magnet of known strength will give us some information on this point. In order to understand how this is, let us consider a simple illustration. Suppose that we wanted to know whether a ball were heavy or light, without being able to weigh it directly. If it were thrown, and a wind of known strength were blowing across, we could find out something about its mass from the amount by which it was

blown out of the straight line. We could, however, definitely calculate its mass only if we knew the force which the wind exerted on it, and the speed with which it was travelling. In the same way, in the electrical case, the deflection by a *magnetic* field gives us the mass of the flying particle only if we know its speed and the force which the magnet exerts on it, and we cannot calculate this force unless we know the charge on the particle.

The amount by which an *electric* force, such as that produced between two condenser plates charged to different potentials, sweeps the particle aside can also be measured, and tells us something more: in fact, the electric and the magnetic deflections together enable us to calculate both the velocity of the particle and the ratio of the charge to the mass of the particle, although not both the charge and the mass separately. In terms of our illustration, we blow the cathode stream aside by two different kinds of wind, obeying different laws, since the force due to the magnetic field acts by virtue of the movement of the charges, and is at right angles to the directions of the field, while the force due to the electric field acts by virtue of the charges alone, and is in the direction of the electric field. It was by exposing the cathode stream simultaneously to the action of an electric and of a magnetic field that Sir J. J. Thomson, the famous head of the Cavendish Laboratory in Cambridge from 1884 to 1919, and Nobel prizeman in 1906,[1] first determined the speed, and the ratio of

[1] On the occasion of a visit to America, Sir J. J. Thomson, who was at the University of Princetown, found that it was impossible for him to get to New York by any ordinary means in time to catch his boat home. An offer was made to him by the competent authorities to stop the transcontinental express from the West Coast to New York. They

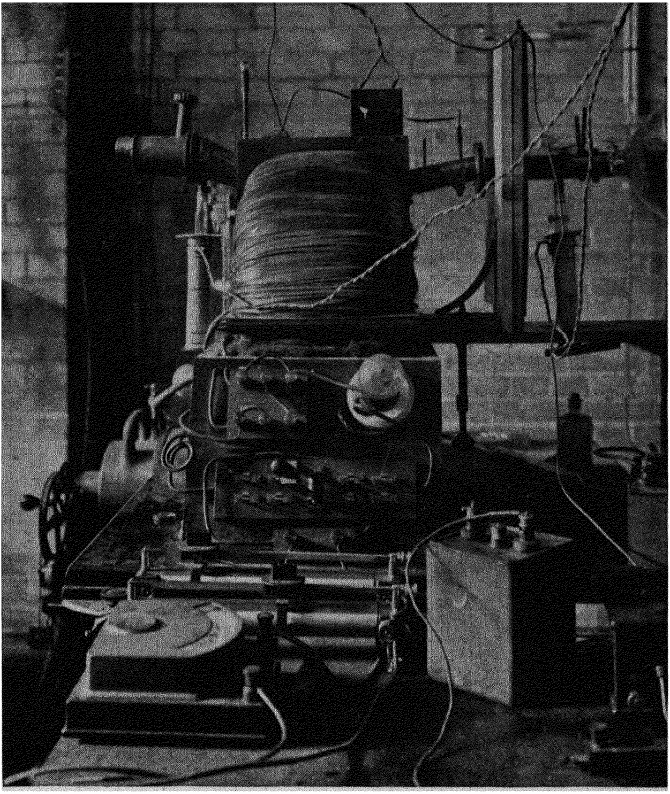
charge to mass, of the flying particles. He saw at once that the figures which he obtained made it most unlikely that they were charged atoms of matter: they must be something lighter.

If we could find the magnitude of the charge on one particle we should know its mass as well, since the method just described gives us the ratio of the charge to the mass. This was done in Cambridge many years ago by a very ingenious method. However, more accurate measurements of the charge have been made more recently in America by Professor Millikan, now Director of the Norman Bridge Laboratory in California. His method will be described at the end of this chapter. We now turn to the further consideration of the nature of the particles which constitute the cathode rays.

The charge on one of these particles turns out to be the same as the charge which we find on atoms by experiments on passing electricity through solutions of metallic salts, but the mass of the particle is much less than (little more than one two-thousandth of) that of the lightest atom known, the hydrogen atom. The particles are, in fact, little atoms of negative electricity all by themselves, not sitting on atoms as they are in liquids, but absolutely free. It may be asked why, in that case, they have any mass at all. The answer is that it can be shown that to move a charge of electricity, if it be concentrated into a very small space, requires a force—

explained that the express had never been stopped for anybody, not even the President of the United States, "but," they said, "we will stop it for J. J. Thomson." The express was duly stopped, and the Cavendish professor caught his boat. Since this story has been doubted I may add that I have it on the highest authority.

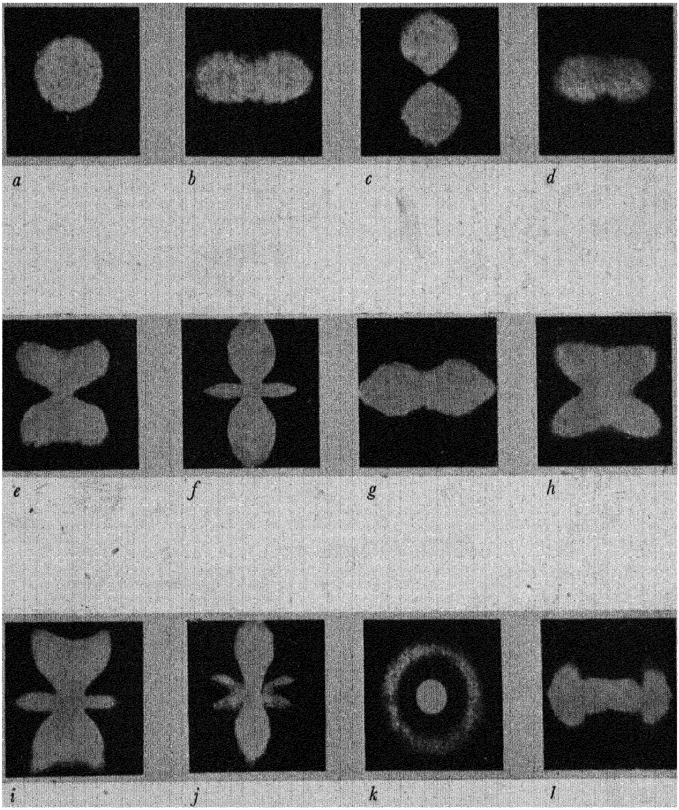
PLATE III



Aston's mass spectrograph.

From Aston's Mass Spectra, *by permission of Messrs. Edward Arnold.*

PLATE IV



Selected possible distributions of electronic charge for the hydrogen atom *after H. E. White.*

that is, the charge tends to resist being made to go faster, or possesses inertia, as we say. In this way it behaves just like an ordinary mass. In fact, if the measured charge be crowded into a minute sphere a little greater than one ten-million-millionth of an inch across, it can be shown that it will have just the mass measured experimentally.

These atoms of pure negative electricity are called electrons. The cathode rays, of which we have spoken, are streams of electrons shot off by repulsion from the cathode within the exhausted tube. Work with such exhausted tubes has led to some of the most remarkable discoveries of modern physics. For instance, if we put inside such a tube a heavy piece of metal opposite the cathode, something very remarkable takes place when the discharge is passed and the stream of electrons strikes the metal, which is called the anode or anti-cathode. The anti-cathode gives out X-rays. Every X-ray tube used in hospitals, of whatever pattern, consists of a lump of metal in a highly evacuated tube, bombarded by very swift electrons. Even if there be no lump of metal we get X-rays, although not very penetrating ones, generated where the cathode stream hits the glass: they are, in fact, produced whenever very swift electrons encounter matter of any kind. The rays which were discovered in 1895 by Röntgen were proceeding from the walls of an evacuated glass tube. This discovery of X-rays was one of the most significant in all modern science, and for it Röntgen received, in 1901, the first Nobel Prize awarded for physics.

The way in which Röntgen came to make his discovery is a striking illustration of the power of the born discoverer to seize upon a chance observation and

develop it to great ends. He was repeating certain experiments on the cathode rays, for which he had been using a small screen covered with barium platino-cyanide, a substance which lights up—or fluoresces, to use the technical term—when cathode rays strike it, and also, as was subsequently proved, when X-rays strike it. With a certain object in view he had covered up a cathode tube with black paper, to exclude all light, and he switched on the high potential to the tube to see

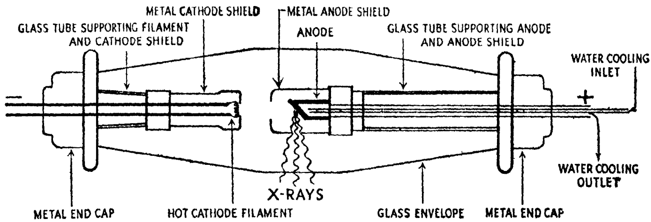


Fig. 1. A modern X-ray tube.

if the light was, in fact, cut off. To his surprise, he noticed that the barium platinocyanide screen, which was some feet away, was shining brightly. It ceased to shine when he cut off the potential from the tube. It was this that led him direct to his astonishing discovery. Long afterwards, when asked what he thought when he noticed the screen glowing, he said, "I did not think, I investigated." This does not mean that great physicists do not think, but that in physical discovery a little carefully designed experimenting is worth a great deal of interesting speculation.

The general construction of a modern X-ray tube is shown in Fig. 1. The source of electrons is a fine wire, or filament, kept hot by the passage of a current. The electrons are accelerated by a high voltage applied

between the cathode on the left and the anode on the right, and therefore hurl themselves at the hollow anode, which is kept cool by water circulating inside it. If it were not for this it would soon melt locally. A high vacuum prevails in the tube. The issuing rays are indicated symbolically by wavy lines.

Another very important use that has been made of the cathode ray stream is for following very rapid changes of electric force. The rate at which any body, any piece of matter, speeds up when a force is applied to it depends not only on the size of the force but also upon the mass of the body. To make the effect of mass clear, you have only to think of the difficulty of moving, say, a ten pound weight rapidly backwards and forwards as compared to that of moving a golf ball rapidly in the same way, even if they are both supported on a smooth table so that no effort is required to hold them up. It would be impossible to move the weight appreciably if we tried to make it vibrate a few times a second: it takes too long to speed it up, check it and speed it up in the opposite direction with the force that we can apply.

In an ordinary electrical instrument the moving part is usually a coil or suchlike, and it is not possible to make it register vibrations taking place rapidly, say, twenty times a second: before the electromagnetic forces have got it moving in one direction they are reversed and tending to make it move in the other direction. Special instruments, so-called oscillographs, have been constructed in which the moving parts are particularly light and well designed, but even here there are difficulties if we want to register changes of current or electric force which reverse thousands of

times a second. In modern developments we often have to deal with changes taking place in a millionth of a second or so.

In the cathode ray stream the moving electric charges are associated with extremely minute mass, whereas in the case of an electric current in a wire we have moving electric charges which can only indicate forces acting on them by taking the comparatively

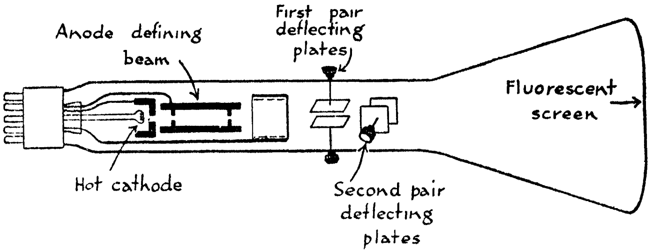


Fig. 2. A cathode ray oscillograph.

heavy metal with them. A consequence of the very minute electronic mass is that the cathode ray stream is ideal for following accurately very rapidly changing electric forces. The piece of apparatus in which it is utilised for this purpose is known as the cathode ray oscillograph, and a diagram illustrating its construction is shown in Fig. 2. The beam in the evacuated tube passes between first one pair of little parallel plates and then another pair, so arranged that an electric force applied between the first pair is at right angles to that applied between the second pair, and both forces are at right angles to the direction of the beam. The cathode particles—electrons—strike a surface spread with a preparation which glows brightly under their impact, so that we have a bright spot whose movement indicates at once the movement of the cathode stream.

The phosphorescent preparation continues to glow for a very short time after the ray has moved from the spot, so that the motion of the cathode stream is indicated by a bright line on the screen. This "memory" of the phosphorescent screen for what happened a fraction of a second or a second ago has important applications.

Often an electric force is applied to one pair of plates in such a way that the spot moves uniformly across the screen, tracing out a horizontal base line, and then returns instantaneously to where it started from and repeats the process. To the other pair of plates is applied the electric force which it is wished to record or observe. It moves the beam at right angles to the base line, so that signals are instantaneously indicated by up and down flicks. If we know the rate at which the base line is being traced out—and it may be such that the spot runs right across the screen in a thousandth of a second or so—the distance between two flicks gives us the time interval between the signals, correct to less than a millionth of a second. This is all due to the extreme mobility of the cathode stream.

The kind of arrangement just described was a essential feature of radar sets during the war, the interval measured being that between the sending out of a signal and its return when reflected from an aeroplane. As the total time of travel there and back is only just over a thousandth of a second when the aeroplane is one hundred miles away, it can easily be realized that very accurate time measurement is essential. A change of a millionth of a second corresponds to an approach of the aeroplane by one hundred and fifty yards or so.

The cathode ray oscillograph is also an essential part of television sets, where the beam traces out four hundred and five horizontal lines in a twenty-fifth of a second, and indicates rapid changes from light to dark as it runs along each line, thus building up the picture. It was also the paintbrush, so to speak, that traced out the picture in the wonderful devices, carried in our bombers, which gave a picture of the ground even when cloud cut off all ordinary light. Short wireless waves can penetrate cloud and mist: they were sent out from the aeroplane, and could be made to indicate, through the cathode ray beam, the kind of ground from which they were reflected. The arrangement was, in essence, a kind of television with wireless waves instead of light waves, attended by a consequent loss of definition. These few examples may serve to indicate the important applications that have been made of the cathode ray beam.

Electrons can be obtained from a variety of sources in a variety of ways. If any metal be raised to red heat, it gives off electrons. A very familiar instance of this is the so-called thermionic valve used, for instance, in wireless receiving sets. Such a valve contains a wire which is heated by the passage of an electric current, and this wire gives off a swarm of electrons, which is utilized to magnify the electrical effects which it is desired to observe—namely, the changes in the electric force produced by the broadcasting waves. The electrons for the cathode ray beams are usually produced by a hot wire in X-ray tubes, and always have this origin in cathode ray oscillographs.

Electrons are also set free from metals when violet or ultra-violet light, or X-rays, fall upon them, a fact

which has been utilized in the so-called photo-electric cells for measuring the strength of weak lights, since the stronger the light, the more electrons are given off, and the supply of electrons can easily be measured as an electric charge. In whatever way, or from whatever substance, the electrons are produced, they are always the same atoms of electricity—that is, they have the same charge and the same mass. The electrons produced in a tube containing a trace of hydrogen gas are the same as those in a tube containing a trace of air, and are the same as those produced from a hot wire, whether it be of platinum or of tungsten, and the same as those produced from a plate of metal, whether it be zinc or iron, on which ultra-violet light is falling. The atom of negative electricity is unique and indivisible.

We have spoken of the atom of negative electricity: can we get an atom of pure positive electricity? Until recently the answer was "No." At present, although, as will be shortly explained, the existence of a positive electron is well established, it is still true that in all ordinary laboratory processes only negative electrons are produced. In the case of an exhausted tube flying positive charges can be produced and detected by certain means, but they are always thousands of times heavier than the electron, and prove to be not isolated positive electricity, but atoms of matter with a positive charge. We can, for instance, have positive rays consisting of charged hydrogen atoms, or positive rays of charged oxygen atoms, or positive rays consisting of charged nitrogen atoms. What actually happens is that we can knock or shake one or more electrons, particles of pure negative electricity, out of an atom, and when we do this we leave behind a

positively charged atom. We cannot, by ordinary laboratory agencies, shake a particle of positive electricity out of an atom, and leave behind a negatively charged atom: we can have negatively charged atoms, but they are simply ordinary neutral atoms with one or more extra electrons sticking to each.

Perhaps a fanciful illustration may be allowed. Let us suppose that a man contains two principles, good and evil, and for convenience let us compare the good to positive electricity, the evil to negative electricity. Let us further suppose, without any theological implications, that a normal man contains both principles in equal quantities, so that on the whole he is neither good nor bad. To illustrate the electrical case, we must suppose that we could remove some of the evil from a man as an unattached essence, leaving behind a rather good (positively charged) man, and obtaining the evil principle without a human home. Let us say that we have cast out the devil from the man. We cannot, however, if our illustration is to hold, remove some of the good as a pure essence, leaving a rather bad man: we never hear of casting out angels from a man. Virtue, or positive electricity, must have some material seat. I do not wish to suggest that this analogy has any moral meaning: it is given merely to try to make clear the essential difference between positive and negative electricity.

This is the position as regards ordinary processes by which electrons are produced, and until 1933 it was definitely believed that the positive counterpart of the electron had no existence—a positive charge, not associated with matter, had never been detected. In that year, however, it was found by Anderson in

America and by Blackett and Occhialini in England, that the cosmic rays, falling on matter, liberated from atoms particles of pure positive electricity, the charge being of the same size as that on the ordinary electron, but of opposite sign. These cosmic rays are radiations that enter the earth's atmosphere from outer space. The amount of cosmic radiation is very small, but the rays are exceedingly penetrating, passing through thicknesses of metal which are quite opaque to X-rays as ordinarily generated in a laboratory. It is, no doubt, properties connected with this great penetration that enable them to produce the positive electron or positron, as it is called.

Plate II*b*, due to Fowler and Lauritsen, shows two pairs of electrons, each pair comprising a positive and a negative electron, issuing from a plate of lead which has been exposed to very penetrating radiation. The tracks of the electrons were photographed by the Wilson cloud chamber device, described in Chapter V. The chamber was in a strong magnetic field, the direction of which was at right angles to the plane of the paper. In such a magnetic field the track of a positive electron and that of a negative electron, starting initially in the same direction in the plane of the paper, should curl off one in one direction, and the other in the opposite direction, just as the tracks in the photograph do.

Positrons, as these "positive electrons" are called, have since then been produced in other ways by taking advantage of certain novel discoveries connected with radioactivity. The reason they are so difficult to observe, and that they are never detected as a result of any simple processes such as those which produce

negative electrons, appears to lie in the fact that their free life is very short: they disappear almost as soon as they are freed. While, then, the ordinary electron is a commonplace of the laboratory and of the light electrical industry, the positron is a scientific curiosity of the greatest theoretical interest and importance which, at present, is little understood.

The lightest atom is the atom of hydrogen, and the lightest positively charged atom which we can get is therefore the positively charged atom of hydrogen. It is an atom of hydrogen which has lost an electron—in fact, its one and only electron, for a neutral hydrogen atom only has one. This positively charged atom of hydrogen plays a very important part in modern physics: it is a unit of matter which is often called a proton.[1] We shall have to refer to it frequently when we discuss the structure of the atom.

Electricity is, then, atomic in nature. The atom of electricity cannot be split up, or broken, and all electricity must be supplied in these little units. The atom of electric charge—that is, the charge on the electron—is exceedingly minute. In an ordinary electric lamp some million million million electrons per second pass a given point in the wire. If, instead of having an electric meter, we had to count the individual electrons passing through our lamp filament, it would take all the inhabitants of the earth, counting night and day as fast as they could go, two years to number the electrons which had passed through the lamp in one second. Yet, notwithstanding its smallness, the charge on the electron has been measured with an accuracy of about one part in five thousand. The latest method

[1] Not to be confused with photon—or positron!

involves a somewhat complicated chain of reasoning, but an accurate method used by Millikan is quite simple in principle and we may fittingly close this chapter by describing it briefly. Millikan's work on the electronic charge was so important that he was awarded a Nobel Prize for it in 1923.

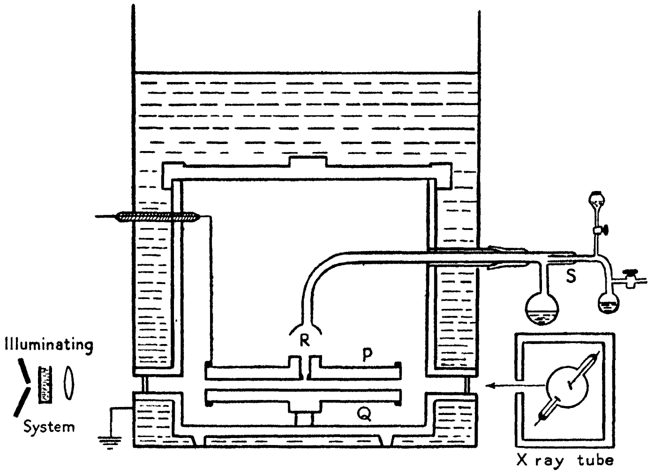


Fig. 3. Millikan's apparatus for finding the charge on the electron.

By means of a spray a mist of minute drops of oil, or of some other liquid, are produced at the opening R: a very few of these droplets arrive through a fine hole in the upper plate in the space between two horizontal metal plates, P and Q, which can be electrically charged (Fig. 3.) In the ordinary way the droplets settle down very slowly through the air, at a rate which can be accurately measured. The rate depends upon the size —the smaller the droplet the slower it falls in air. By means of X-rays or some other agent, a number of

electrons and electrically charged atoms or molecules are produced in the air surrounding the droplets, and a droplet will occasionally pick up a positive or negative charge—that is, an electron, or an atom with an extra electron or an atom short of an electron. When it does so, it is attracted by one of the charged plates, and, if the electric field be suitably adjusted, the fall of the droplet, whose motion is studied through a microscope, can be checked. It remains suspended, gravity pulling it down, and the electric force pulling it up. Sooner or later, after the droplet has been stationary for some time, it will suddenly begin to move up or down. This means that it has picked up another charge, either positive or negative. The electric force between the plates can then be readjusted, and the droplet kept steady again.

Now if the weight of the droplet be known (and it can be accurately found by its rate of fall in air when there is no electric field) we know the force with which gravity is pulling it down, and if we measure the strength of the electric field, we can calculate what the charge on the droplet must be for it to experience the upward pull which just counterbalances the downward pull of gravity. The experiment is thus very simple in its essence, and merely consists in measuring the electrical pull, exerted by an electric field of measured strength, on a tiny charged drop of oil weighing about a million million to the ounce. In this way Millikan found that the total charge which a droplet can pick up is always one or two or three, or some other very small number of times a unit charge, and never anything in between. The unit charge can be calculated from these experiments, and is found to be just about the

magnitude which had already been found by other ways of the charge on the electron. The value obtained by this method is very accurate. The droplet is so small that it collects only one electron, usually sticking to an atom, at a time. No matter how the electrons and charged atoms be produced, no matter what the nature of the droplet, whether oil or quicksilver, the same result is obtained. We are confident, then, that the unbreakable atom of electricity does exist, and we know the magnitude of its charge with a much greater percentage accuracy than most of us know our own weight.

IV

THE NATURE OF LIGHT

Were I to assume an hypothesis, it should be this, if propounded more generally, so as not to determine what light is, farther than that it is something or other capable of exciting vibrations in the aether: for thus it will become so general and comprehensive of other hypotheses, as to leave little room for new ones to be invented.

ISAAC NEWTON. 1675[1]

Are not the Rays of Light very small Bodies emitted from shining Substances?

ISAAC NEWTON. *Opticks.* Second Edition, 1717

WE shall see when we come to consider the way in which atoms are made that it is necessary to know something about the nature of light. Every kind of light originates in some material source—a glowing solid; an incandescent liquid, such as molten iron; or a gas through which an electric discharge is passing. In other words, every kind of light has its beginning in atoms, and it is not surprising that we can learn something about atoms by devoting attention to light.

A very slight study of the great source of light which nourishes us, the sun, will suffice to tell us some of the most important properties of light. The atmosphere which surrounds our earth is a comparatively thin layer, for at a height of ten miles the air is only one-tenth as dense, and at a height of a hundred miles is already only one ten-thousand-millionth as dense, as it is at the

[1] See Thomas Birch, *History of the Royal Society.*

surface of the earth. The sun, however, is about ninety-three million miles distant. This shows us that light must be able to pass freely through absolutely empty space where no atoms are, in contradistinction to sound, which requires an atmosphere of some kind, or a solid, or a liquid, to convey it. Further, we know that sunlight heats bodies on which it falls: in fact in Egypt there are engines which are worked by the aid of the rays of the sun, concentrated by concave mirrors on to metal boilers. This shows us that the rays which traverse empty space are a form of energy, since we know that heat is a form of energy, and anything which can be turned into heat must itself be a form of energy.

The speed with which light travels can be measured either from certain astronomical observations, or by very accurate experimental methods which have been worked out. It is very great, about 186,000 miles a second, which means that the light from the moon takes about one and a fifth seconds, while that from the sun takes some five hundred seconds to reach us. It may be remarked in passing that stars are so far distant from us that the time taken by light to reach us from even the nearest stars is measured in years.

Light, then, is a form of energy which traverses space where no matter is, with a very high speed. Now Sir Isaac Newton first showed how sunlight could be spread into a coloured band, or spectrum, by means of a prism, and proved that all the colours of the spectrum must be contained in the sunlight and merely separated out by the prism. The colours of the spectrum form a continuous range, in which the following can be seen as distinct by a man with ordinary good colour vision:

red, orange, yellow, green, blue, violet, in that order.[1] It is found, however, that there are rays beyond the red which are invisible to the eye, but can be detected by their heating effects: these are the so-called infra-red rays. The large heating effect means that most of the energy of the solar spectrum lies in the infra-red. Similarly, there are invisible rays beyond the violet: these have a comparatively very small heating effect, but have certain other actions on matter, of which the most notable is that they affect a photographic plate just as visible violet light does. They are called the ultra-violet rays, and it is characteristic of the vigorous action, of a chemical nature, which they can produce, that the sunburnt colour of people exposed to the summer sun is due to a narrow region of ultra-violet rays, and not to the heat or the visible light. In the ordinary sense sunburn is not a burn at all, for heat has nothing to do with it: it is, in nature, more like the changes of colour which light produces in certain chemicals, or in coloured fabrics when they fade.

Now it is known that light has the properties of a vibration, or wave motion. One of the most straightforward experiments for showing this was devised by Thomas Young and described by him in 1807. Light coming from a slit S a long way to the left (not shown in the diagram) falls on a card in which are two small slits A and B. (Fig. 4.) The light spreads out from these slits if they are fine enough and overlaps in the region of a screen PQR. This region

[1] The colours of the spectrum are usually given as red, orange, yellow, green, blue, indigo, violet, but many people of good colour vision do not see indigo as a really distinct primary colour, but only as a kind of blue.

instead of being uniformly illuminated, is found to be crossed by brilliantly coloured bands, parallel to the slits. The explanation can be seen from the diagram. Any wave of light starting from S will reach A and B with the waves in step, since the distances from S to A and from S to B are the same, so that waves which leave A and B on the right are in step.

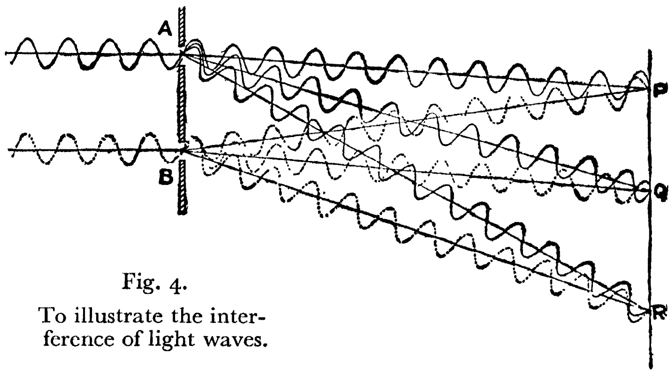


Fig. 4.
To illustrate the interference of light waves.

At P, which is equidistant from A and B, the waves will likewise be in step. At Q, however, which is nearer to B by half a wave-length than it is to A, the waves will be exactly out of step, as shown, a crest of one exactly cancelling a trough of the other, and so on, at every instant. Hence at Q there should be no motion, which means no light—darkness. At R, which is nearer to B by a whole wave length than it is to C, the waves will agree again, crest with crest and trough with trough, and we have bright light.

Now to the different pure colours of the spectrum correspond different wave lengths: a particular fixed wave length produces on the normal eye a particular fixed colour effect. Hence if the light which falls on

S is of one particular wave-length only, say a wave-length in the red region, then on the screen at P and R will appear red bands separated by dark lines. If light of another wave-length—say, one in the green region—falls on S, there will be green and dark bands, but these will be in a different position to the red bands, since the position of Q and R is, as we have seen, governed by the wave-length. The same considerations hold for light of all wave-lengths. If therefore white light, which contains a whole range of wave-lengths, falls on S, we shall expect a series of brightly coloured bands of various hues, which is what is found.

This apparent reinforcement and destruction of light, made evident in Young's experiment, is called interference, and can be demonstrated with all waves under suitable conditions—wireless waves, for instance, as well as light waves. No light is really destroyed, but the light energy is redistributed on the screen: what does not appear in the dark interference bands is heaped up at the bright bands. Some little attention has been devoted to these experiments, because demonstrations of this kind started the wave theory of light, which pervades modern physics. The wave-length of light of different kinds is measured by certain experiments based on interference.

The wave-length of visible light is extremely minute. For deep red light, which has the longest waves of the visible spectrum, the wave-length is about thirty millionths of an inch, for green light about twenty millionths of an inch, and for violet light about sixteen millionths of an inch. The ultra-violet comprises still shorter wave-lengths, while the wave-lengths of the infra-red are longer than those of the extreme visible

red. That we see only a certain restricted range of wave-lengths is due to the constitution of our eye, and not to any inherent property of these particular waves.

Light, then, has the properties of a wave-motion, which traverses space in which there is no material substance whatever, not even the most rarefied gas. In order to obtain some sort of an explanation of this vibration passing through emptiness, the idea of an ether of space was evolved, the said ether being supposed to be some non-material substance, which filled all space, whether the space was empty, in the ordinary sense, or occupied by matter. If the space was occupied by a substance, the ether was supposed to pervade the gaps between the atoms of the substance, as the air pervades the space between the trees in a forest. The ether was gifted with the property of being able to vibrate, just as a jelly filling all space would vibrate if given a shock at any point, which point would become the centre of waves spreading out in all directions.

The ripples which spread out over the surface of a pond when a stone is dropped in give an even simpler representation of the light-waves spreading out from a source of light. However, it is difficult nowadays to maintain the existence of an ether of space with the properties of an ordinary elastic solid, for if such an ether really existed, we should be able to measure our passage through it, and find out if we were moving, not with reference to other material bodies, but with reference to the universal ether. Delicate experiments and the theory of relativity tell us that we cannot do this, so that to-day it is usual to say that light-waves travel through empty space, but that we do not know

how they do it, although we know the speed with which they travel. They leave the light source, and after an interval of time they appear at the eye or the observing instrument. Clearly we can only tell what is happening at the point where our eye or instrument is. How the light behaves while on its way from a material source to a material means of observation is a matter on which we cannot experiment: we can only form reasonable conjectures.

Now visible light, with its close companions, the ultra-violet and the infra-red, is not the only kind of radiation that travels through empty space. The waves of wireless telegraphy and broadcasting do the same, and actually travel at the same speed as light. Their wave-lengths are, however, enormously greater than those of light, being usually measurable in yards and hundreds of yards rather than in hundred-thousandths of an inch. X-rays also travel through empty space, and have been proved to be waves, but of wave-length much shorter than even the ultra-violet. Classes of X-rays of different penetrating powers are known, and the shorter the wave-length of the X-rays the greater their power of penetrating. Those used in hospitals in the ordinary way have a wave-length of a few hundred-millionths of an inch. Radium gives out a class of rays called gamma-rays, which are just like X-rays, but still more penetrating, with wave-lengths as short as twenty-two million-millionths of an inch. Cosmic rays contain radiations corresponding to still shorter wave lengths.

We have, then, various classes of waves which pass through empty space: their properties depend upon the wave-length. The ultimate nature of all these

waves is the same: they all originate in some kind of electrical disturbance, even the light waves, as we shall see later, and their passage is characterized by a rapid oscillation of electric and magnetic forces. As a water wave passes us, the height of the water at a given place increases and decreases alternately, and goes on doing so as long as the train of water waves is kept up. The water does not travel on with the waves: if a stone is dropped into a pool, the water that was at the place where the stone fell does not move out with the ripples, but stays where it was, bobbing up and down, and in the same way the water at other places bobs up and down. What travels out is the state of motion, handed on from one water particle to the next with a slight delay. If soldiers are dressing by the right, and the right hand man makes a small move forward, a ripple will run along the line. If he keeps on moving backwards and forwards periodically, and the men keep on dressing by him, a wave will run along the line. The individual man, however, remains in roughly the same position.

In an electromagnetic wave the electric force at any point swings to and fro, diminishing from being large in one direction to being nothing, and then reversing until it becomes large in the opposite direction, when it again diminishes, and so on. Changes of electric force are always, by their very nature, accompanied by changes of magnetic force which take place at the same rate, which is why the waves are called electromagnetic. All electromagnetic waves travel in empty space with the same velocity, that of light. Wireless waves and X-rays both originate in an artificial electric disturbance produced by our control of

electrical apparatus, and both are electromagnetic waves, just as Atlantic rollers and the pond ripples on a calm day are both water waves. The wave-length of the wireless wave is about a million million times that of the X-ray, and this difference of wave-length is what gives the difference of properties. The following table indicates the wave-lengths of the different classes of waves; but, of course, there is no hard and fast limit to be set for any particular kind of waves. The terms are general ones, like "dwarf" and "giant," and it is difficult to know whether, for example, to call a borderline radiation a short ultra-violet or a long X-ray radiation, just as it may be difficult in a particular case to know if a man is a very short ordinary man or a very tall dwarf.

Electromagnetic Waves

Kind of Wave	*Wave-length*
"Wireless" waves, including radar	20 miles to 1 inch or so, say 1,300,000 inches to 1 inch.
Waves produced by other electrical oscillators	100 inches to 1 hundredth of an inch.
Infra-red	1 hundredth of an inch to 30 millionths of an inch.
Visible light	30 to 15 millionths of an inch.
Ultra-violet	15 to ½ millionths of an inch.
X-rays	500 to 1 thousand-millionths of an inch.
Most penetrating gamma-rays	22 million-millionths of an inch.[1]

On the opposite page is a lively pictorial representation of the electro-magnetic spectrum taken from an American book, Lunt and Wyman's *Electricity for Everybody*.[2]

We have discussed the atom of matter and the atom

[1] The longer gamma-rays coincide with certain short X-rays.
[2] By kind permission of The Macmillan Company.

. . . ELECTROMAGNETIC SPECTRUM . . .

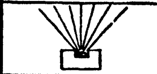
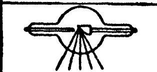
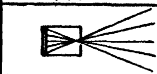
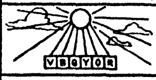
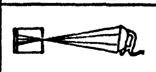
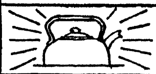
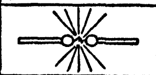
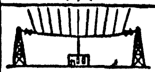
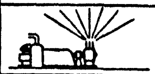
NAME	SYMBOL	SOURCE	WHAT THEY DO
COSMIC RAYS		SHORTEST WAVES BOMBARD EARTH FROM OUTER SPACE	IONIZE GASES
GAMMA RAYS		GIVEN OFF BY RADIUM AND OTHER RADIOACTIVE SUBSTANCES	USED IN CANCER TREATMENT
X RAYS		X-RAY TUBE	TAKE PICTURES OF BROKEN BONES DETECT FLAWS IN MACHINERY
ULTRAVIOLET		SUN AND ELECTRIC ARC	• TAKE PICTURES • • CAUSE TAN • DESTROY MOLDS AND BACTERIA
VISIBLE LIGHT		SUN AND OTHER STARS INCANDESCENT LAMPS	MAKE VISION POSSIBLE
INFRARED [SHORT]		RADIATED FROM HOT OBJECTS	PHOTOGRAPHY • PENETRATE HAZE • TAKE PICTURES IN TOTAL DARKNESS
HEAT INFRARED [LONG]		RADIATED FROM HOT OBJECTS	THE HEAT YOU FEEL FOR WARMTH, COOKING, ETC.
SHORT ELECTRIC		ELECTRIC SPARKS AND ARCS	FORMERLY USED IN WIRELESS
RADIO		RADIO VACUUM TUBE	TRANSMIT SOUND AND PICTURES BY RADIO
VERY LONG WAVES		ALTERNATING CURRENT GENERATOR	LIGHT, HEAT, AND POWER

Fig. 5. Pictorial scheme of the Electromagnetic Spectrum.

of electricity. Is there such a thing as the atom of radiant energy? Various lines of investigation have culminated in the so-called quantum theory, which answers this question in the affirmative. It appears that we cannot have radiant energy given out in small quantities of any size whatsoever, but that there are

small units of radiation, and that whenever we have an emission of light, it consists of one or a number of these units. Just as if we buy tobacco in the form of cigarettes we cannot purchase less than a certain weight of tobacco, but must always have at least one cigaretteful, and, in any case, a whole number of times a cigaretteful, so when we receive radiant energy in the form of radiation we cannot have less than a unit, or quantum, as it is called, of energy.

However, the unit of radiant energy has the peculiar feature that it is not of a fixed and determined size for all kinds of radiation, but depends upon the wave-length of the radiation. It is easier to discuss this point if we speak of the frequency of the radiation, which is the number of vibrations a second. As the velocity of all kinds of electromagnetic radiation is the same in free space, it can easily be seen that the longer the wave-length the smaller the frequency. Thus, the frequency of a wireless wave whose wave-length is 100 yards is $186{,}000 \times 17{\cdot}6 = 3{,}273{,}600$ vibrations a second, since the velocity is 186,000 miles per second; while the frequency of a kind of violet light, whose wave-length is sixteen millionths of an inch, is $186{,}000 \times \frac{1{,}760 \times 36}{16} \times 1{,}000{,}000 = 186{,}000 \times 110 \times 36{,}000{,}000 = 736{,}560{,}000{,}000{,}000$ vibrations a second! The frequency of X-rays may be many thousands of times as great.

Now the unit, or quantum, of radiant energy is obtained by multiplying the frequency by a certain fixed number (called Planck's constant, after the German physicist who originated the quantum theory, and was awarded a Nobel Prize in 1918), which is

very, very minute, so that even when huge numbers like that just cited are multiplied by it the result is still very small. This means that the quantum, or unit quantity, of X-ray energy is many thousands of times as great as that of visible light, which again is many millions of times as great as that of wireless-wave energy. To continue our cigarette analogy, it is as if cigarettes of the most diverse sizes existed, some as big as a steamship funnel and others of the smallest size, so that when we bought one kind, the large kind, our unit weight of tobacco was tons, while when we bought the other, it was in a small fraction of an ounce. For a given size of cigarette (corresponding to a fixed frequency, or wave-length) we should, however, only be able to buy tobacco in steps of weight—half a cigarette is not sold. Half a quantum of radiant energy cannot be emitted.

A special name has been given to the quantum packet in which radiant energy is emitted and absorbed, which emphasizes its atom-like nature. It is called a photon, from the Greek word *photos*, meaning "of light," the same word that appears in "photography," for instance. It does not, of course, apply only to quantum packets of light, but to all electromagnetic radiations: one can have a photon of X-rays. The word must not be confused with the proton, which is the hydrogen nucleus.

We have pointed out that the main energy of the spectrum lies in the infra-red, but here the frequency is small compared with that of the ultra-violet, so that, in accordance with what has just been stated, the energy quantum is larger in the ultra-violet and smaller in the infra-red. Is there a contradiction here?

No, since so very few units are given out, comparatively speaking, in the ultra-violet that, although they are individually big, the total energy which they all contribute is small. Speaking in terms of cigarettes once more, one occasionally used to see exceptionally large cigarettes, some five inches long, exposed for sale. They contained, individually, much more tobacco than ordinary cigarettes, but so few of them were sold that the total weight of tobacco used per year for making large cigarettes was very small compared with that used for those of ordinary size. The chemical activity of the ultra-violet is an expression of the fact that the energy quantum involved when the radiation acts on a molecule is large: the energy,or heating effect, in the ultra-violet part of the spectrum is small, because there are comparatively few quanta there.

What has just been stated about the quantum of radiant energy is the result of a prolonged consideration of certain experimental results, and not of argument as to what ought to be true. We cannot see any particular general reason why energy should thus be radiated in bundles, as it were, and not in any amounts whatsoever. Everything, however, points to such a granular emission rather than a continuous emission, just as all experiments indicate that matter has a granular structure and not a continuous structure. Since all matter consists ultimately of atoms, all radiation of energy by matter must ultimately be a radiation from atoms, but we must imagine radiant energy being thrown out from an atom in pailfuls, as it were, rather than from a hose pipe. A pailful is called a quantum of radiant energy, and the size of the pail depends upon the wave-length of the radiation.

The conclusions of modern science, then, are as follows:

1. All matter consists ultimately of atoms, and there are over ninety different kinds of atoms, corresponding to the different chemical elements. All known substances which are not chemical elements are formed ultimately by the combination of chemical elements—that is, by the combination of atoms.

2. Negative electricity is made up of atoms of pure negative electricity, called electrons, which can have an existence independent of matter. All negative electrons are of the same kind, whatever their source. Positive electricity is generally found in combination with matter, and all positively charged atoms of matter are merely atoms which have lost one or more electrons. A positive electron, or positron, can exist under exceptional conditions.

3. All radiant energy is of an electro-magnetic character, and can be emitted by atoms only in separate packets of energy, called quanta. The amount of energy in a packet depends upon the frequency of the radiation, being, in fact, proportional to this frequency.

We have then three different kinds of atoms: the atom of matter, the atom of electricity, and the atom of radiation. We can now proceed to inquire how these three are combined in the modern theory of the structure of the atom.

V

THE STRUCTURE OF THE ATOM

In 1911 Rutherford introduced the greatest change in our idea of matter since the time of Democritus.

A. S. EDDINGTON. *The Nature of the Physical World.* 1928

But it is necessary to insist more strongly than usual that what I am putting before you is a model—the Bohr model atom—because later I shall take you to a profounder level of representation in which the electron, instead of being confined to a particular locality, is distributed in a sort of probability haze all over the atom.

A. S. EDDINGTON. *New Pathways in Science.* 1935

. . . how build, unbuild, contrive
To save appearances, how gird the Sphere
With Centrick and Eccentrick scribl'd o'er
Cycle and Epicycle, Orb in Orb.

MILTON. *Paradise Lost.* VIII

UNTIL the past century was nearing its close, it was generally believed that every atom was a complete unbreakable particle, a "manufactured article," as Clerk Maxwell called it, which was exactly like every other atom of the same element. It was also believed that the eighty odd different kinds of atoms then known were eighty different patterns, or models, as it were, which had nothing in common with one another, so that, to use an engineering simile, they resembled eighty different kinds of castings made from eighty different kinds of moulds, rather than eighty different

structures, all built up from the same kinds of bars and rivets, arranged in different ways. If we believe to-day that the latter analogy represents the true state of affairs, it is because the advance of knowledge has revealed to us the existence of minute entities which can play the part of the bars and rivets, while fifty years or so ago there seemed to be no materials for atom building.

It is true that more than a hundred years ago an English chemist, Prout, suggested that all atoms were assemblies of numbers of the lightest atom—namely, the hydrogen atom—arranged in different ways. If this were true, however, we should expect all the heavier atoms to weigh some exact number of times a hydrogen atom, just as if a structure were built up of a number of similar bars (the weight of the rivets being negligible) it would weigh an exact number of times the weight of one bar. It is found, however, that the atomic weights are not in general exact multiples of the atomic weight of hydrogen, nor of any weight of that kind, but have in general fractional parts. As we do not admit that a hydrogen atom can be broken into smaller atoms, this question of fractional parts in the atomic weight would appear at first sight to put out of court the suggestion that the hydrogen atom is a unit, from numbers of which heavier atoms can be built. We shall learn, however, that the researches of recent years have provided a solution which makes it acceptable.

Electrons can be obtained from any kind of matter, solid, liquid, or gas—that is, from any kind of atom, in any state—and they are very much lighter than any kind of atom, a single electron having a mass little more than one two-thousandth of the mass of the

hydrogen atom. It is therefore clear that the electron must be a constituent part of the structure of all atoms. But electrons have a negative charge, so that, since atoms as a whole have no charge in the ordinary way, each atom must contain a positive charge to neutralize or annul the negative charge of the electrons. The whole modern theory of the structure of the atom deals with the arrangement of the positive and negative electrical charges in the atom. We will first of all describe briefly how the atom is built, and then refer to one or two of the experimental investigations which have given us this knowledge.

Even the heaviest atom contains only ninety or so electrons, while the lightest atom, hydrogen, contains only one. We have already mentioned that the mass of the hydrogen atom is nearly two thousand times that of the electron, while the mass of the heaviest atom, uranium, is about 238 times that of the hydrogen atom. Hence it is clear that the atom cannot owe its mass to the electrons in it, but must have another constituent part, much more massive than the electron. All the evidence goes to show that this heavy part is associated with the positive charge, and that an atom is a structure of the following kind, as first demonstrated by Lord Rutherford, who was awarded a Nobel Prize as long ago as 1908 for his work on radio-activity.

At the centre of the atom is a positively charged particle, called the nucleus, which is very much smaller than the atom itself; in fact, only about a ten-thousandth as big across. This nucleus is the heavy part of the atom, that is to say, in it is concentrated practically all the mass of the atom. Round it are clustered electrons, which rule a certain space surrounding the

nucleus. According to the original theory of Bohr, who first elucidated the behaviour of the part of the atom outside the nucleus, each electron described an orbit round the nucleus, just as the planets describe orbits round the sun. On the latest form of the theory, due to Schrödinger, each electron must be considered as in some way smeared out round the nucleus, in a kind of vibration: there is, so to speak, a certain probability of it being in the neighbourhood of a particular spot at any particular moment, just as there is if it describes an orbit, but there is an element of uncertainty as to where it is at the moment, which is not the case with a strictly defined orbit. The new theory, called the theory of wave mechanics, is very difficult and cannot really be explained without mathematics. It is often convenient to use the older theory of electron orbits, and in many cases it expresses the facts as well as the newer theory. We discuss the matter further in the next chapter.

The number of electrons is such that, when the atom is in its normal state, their joint charge just annuls the positive charge in the nucleus. These electrons can be divided into groups, according to the energy which they possess: on the whole, the further the electrons are from the nucleus, the less the energy of binding—that is, the easier it is to remove them from the attractive field of the nucleus. Roughly speaking, the different electron groups correspond to different average distances from the nucleus. The size of the region in which the outside electron group is distributed is what we call the size of the atom. This "group" consists of only one electron for certain chemical elements—the alkali metals lithium, sodium, potassium and so on.

For other elements it contains more electrons. Somehow or other these outside electrons guard the space they control from intrusion by the outside electrons of other atoms in ordinary circumstances. It is in this sense that they fix the size of the atom. For their work on the theory of atomic structure both Niels Bohr and Erwin Schrödinger were awarded the Nobel Prize, Bohr in 1922 and Schrödinger in 1933.

Instead, therefore, of thinking of an atom as a solid sphere, we may think of it rather as a plum, round which a swarm of gnats occupy a certain space, gnats of bellicose disposition who prevent gnats belonging to other plums from coming within the sphere which they guard. Supposing the size of a plum to represent the size of the nucleus, the space occupied by the gnat swarm will be about two thousand feet across. The atom is mostly empty space, and what little there is in this space is electricity.

The hydrogen atom is the lightest and simplest of all atoms. It consists of a nucleus whose mass is practically that of the whole hydrogen atom, with a unit positive charge, by which we mean a positive charge whose amount is the same as the amount of negative charge on a single electron. Round this a single electron distributes itself, which it does on the older theory by moving in an orbit. The hydrogen nucleus is so important for the question of atomic structure that a special name has been given to it. It is called a proton.

There is another particle which is of great significance in questions of atomic structure. It has the same mass as the proton, but no charge at all; it is called the neutron, to express the fact that it is electrically

neutral. It is produced in various nuclear reactions to which we shall have occasion to refer later. The earliest neutrons were obtained by bombarding beryllium with the alpha particles from radon, which is a radioactive element produced by the natural transmutation of radium. Effects due to neutrons were first observed by Bothe and Becker in Germany, and by Joliot and Irène Curie-Joliot in France, but it was left to Chadwick, now Sir James Chadwick, to discover in 1932 the nature of the particle. For this work he was awarded the Nobel Prize for physics in 1935.

The neutron has very remarkable properties. Since it has no charge, electrical forces have no action on it, and, as a result, it passes through everything, even dense solids, with great ease, for the stopping of electrified particles—and of electromagnetic waves—by matter is all a result of a reaction between the particles—or waves—and the electric charges that make up matter. Neutrons can, for instance, traverse a layer of lead one foot in thickness with ease. They can also, as we shall see later, penetrate easily into atomic nuclei and produce atomic transmutations.

Since practically the whole mass of the atom is concentrated in the nucleus, the heavier kinds of atoms have heavier nuclei. The positive charge on the nucleus also increases when we go from light atoms to heavy ones, but it is found that the number of units of positive charge is always much less than the number of units of mass.[1] It is natural to inquire if each different kind of heavy nucleus is a fresh entity, or whether all

[1] The mass of the proton (more accurately, one sixteenth of the mass of the oxygen atom, which is nearly one per cent. less) is taken as the unit of mass in dealing with atomic structure.

the heavier nuclei are built up of simpler units. Our two possible units of mass are the proton and the neutron, one with a positive charge and the other uncharged. It is clear that by supposing a number of neutrons combined with a number of protons we can build up in imagination nuclei in which any number of units of positive charge are associated with a greater number of units of mass. We actually know now that nuclei are composed of protons and neutrons, but at first sight there would appear to be a difficulty which we will now consider.

The atomic weights of the elements give the weights of their atoms in terms of the hydrogen atom. Thus the atomic weight of chlorine is 35·46, which means that a chlorine atom has average mass 35·46 times that of a hydrogen atom, and the atomic weight of iron is 55·84. But since the proton and the neutron have the mass of the hydrogen atom, if nuclei were made up of them we should expect the atomic weights to be whole numbers and not to have fractional parts. The explanation of this difficulty is based upon one of the most important discoveries of modern physics, that of isotopes.

The net positive charge on the nucleus fixes the number of electrons distributed round the nucleus. This in its turn fixes the chemical properties of the atom—that is, the way in which it combines with other atoms. For since when atoms are chemically combined they are held together by electric forces, the combining properties must be governed by the number and arrangement of the outside electrons of the atom, and this is determined by the total number of electrons present. Now if we suppose that in some way or other a neutron is added to the nucleus, the mass will be

increased by one unit, but the nuclear charge will not be changed, so that we shall have a heavier atom, with the same chemical properties as a lighter atom. If two neutrons be added, the mass is increased by two units, but once more the nuclear charge, and hence the chemical properties, is unchanged. This theory, then, allows us to account at once for the existence of atoms of the same chemical properties, but different masses. Such atomic species are called "isotopes," which means elements having the *same place* (Greek *isos*, equal, and *topos*, place) in the table which expresses chemical properties. Before the discovery of isotopes, it was always supposed that all atoms possessing the same chemical properties had identically the same mass—in fact that all atoms of a given chemical species were identical in all particulars.

The existence of atoms of different masses endowed with the same chemical properties was first established by Frederick Soddy in 1910, on the basis of results obtained with certain radioactive elements. For his general work on radioactivity he was awarded a Nobel Prize in 1921. Since then the fact that most elements, as ordinarily found, consist of mixtures of isotopes has been experimentally proved in the most conclusive fashion. By working with evacuated tubes, in which, by suitable arrangement, a stream of flying atoms with positive charges can be obtained, passing in the opposite direction to the flying electrons which constitute the cathode rays, the masses of the atoms of a gas introduced in minute quantities into the tube can be measured. This was first done by Sir J. J. Thomson. His work was very much extended by F. W. Aston, who devised new and very accurate methods of applying

electric and magnetic fields to measure the mass of the flying atoms, for which work he was awarded a Nobel Prize in 1922. He showed that in ordinary chlorine gas, for instance, there were some atoms whose mass was 37 units, but a smaller number whose mass was only 35 units, the proportion being such that the *average* mass was 35·46. All elements whose atomic weights contain fractional parts are similarly mixtures of atoms of different whole number atomic weights, all having the same chemical properties. Sometimes

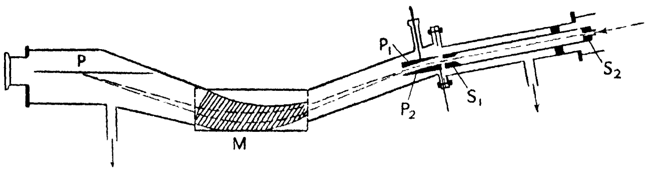


Fig. 6. Scheme of Aston's apparatus, the so-called mass spectrograph.

there are a large number of different masses for atoms of the same chemical properties: there are, for instance, tin atoms of eleven different masses, all chemically identical—that is, there are eleven isotopes of tin.

In Aston's apparatus the charged atoms from an evacuated bulb on the right (not shown) have all kinds of velocities. They pass through two slits S_1, S_2 (Fig. 6), which isolate a narrow beam, and enter the electric field between the charged plates P_1 and P_2, which carries out a preliminary sorting. The beam then passes through a magnetic field whose direction is at right angles to the plane of the paper, created by shaped pole-pieces whose outline is shown at M. This field brings all atoms having a certain mass to a focus at a particular point of the photographic plate P, and atoms

having other masses to a focus at other points of the plate. The photograph therefore shows a series of lines, the position of each of which corresponds to a particular mass. The whole apparatus is, of course, evacuated, to give the charged atoms a free run. In

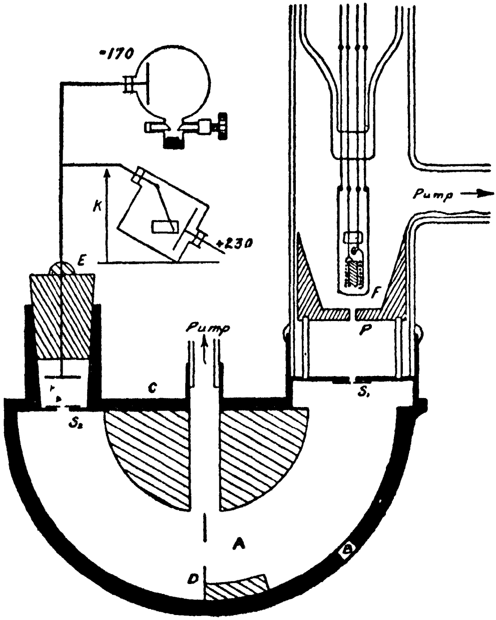


Fig. 7. Dempster's apparatus for detection of isotopes.

the photograph of the apparatus (Plate III) the main feature that strikes the eye is the electromagnet for producing the magnetic field, but the wide tube that contains the photographic plate will be seen on the left.

The American physicist Dempster applied the electric and magnetic field in another way, using the electric field between the plates P and S (Fig. 7) to

give a fixed velocity to charged atoms proceeding from F, and a magnetic field, at right angles to the plane of the paper, over the semicircular space, to analyse them. The strength of the magnetic field is changed until the path of the atoms is deflected sufficiently to bring them to the slit S_2, when they are detected by an electrometer.

All elements with fractional atomic weights are really mixtures of isotopes; e.g. any specimen of tin ordinarily obtained will consist of a standard mixture of the whole eleven isotopes. The isotopes cannot, of course, be separated by chemical means, since they all behave in the same way towards all chemical tests. If there are several different men of the name of John Smith, it is no good expecting to separate them by having a roll called. There are, however, certain non-chemical methods of separating isotopes, which make use of the difference of mass of the atoms, but they are very slow and laborious. A great part of the enormous plant put up in connection with the development of the atomic bomb is devoted to the separation of isotopes in pound-weight quantities. A modified form of Dempster's apparatus, just described, on a very large scale, is one of the methods used.

Isotopes of a given atomic species all have the same number of protons in their nuclei, but different numbers of neutrons. The number that determines the chemical behaviour of the atom is the number of protons, the number of units of positive charge, since this it is that governs the number of electrons. The number of the electrons will decide how they are arranged into groups; the arrangement into groups settles the number and the distribution of electrons in

the outer parts of the atom; the number and distribution of these outer electrons determine the nature of the field of electric force near the surface of the atom, and, since all chemical combination is a matter of the electrical forces in the neighbourhood of the surfaces of the combining atoms, the number of protons in the nucleus ultimately determines the chemical behaviour of the atom. This number, the number of units of positive charge in the nucleus, is called the *atomic number*. It is also the number attached to the element if the elements are written down in order of increasing atomic weight and numbered, 1, 2, 3 . . ., beginning with hydrogen as 1.[1] The fundamental significance of the atomic number was first brought out by the work of the brilliant young English scientist, H. G. J. Moseley, who was killed in the fighting at the Dardanelles in 1915, at the age of twenty-seven.

On the other hand, the mass of the nucleus will be given by the number of protons plus the number of neutrons which it contains. This number is called the mass number of the particular isotope in question. Roughly speaking, it gives the mass in terms of the mass of the hydrogen atom as unity: the fact that it does not do so exactly is due to certain refinements which are discussed in Chapter VII. Thus the atomic number gives the chemical behaviour of the element, the mass number expresses the mass of some one isotope. The atomic weight[2] of an element is the average weight of

[1] With one or two trifling exceptions which are easily explained.

[2] Weight being the pull which the earth exerts on a given mass, it would really be better to talk of atomic mass. However, by custom we always speak of atomic weight, and, since the weight of an atom compared to the weight of an atom of hydrogen is, at a given spot, expressed by exactly the same number as the mass of the atom compared with the mass of an atom of hydrogen, it does not make much difference.

the atoms of all the isotopes in their due proportions. Thus, to take a simple case, 76 per cent. of the atoms of chlorine consist of the isotope of mass number 35, and 24 per cent. consist of the isotope of mass number 37. The atomic weight is about $\frac{35 \times 76 + 37 \times 24}{100} = 35{\cdot}48$

One of the most remarkable cases of isotopy is that of hydrogen. Until round about 1930 it was believed that this, the lightest of all gases, consisted of one kind of atom only, having a nucleus, whose mass was taken as unity, with one positive charge—the proton, to which we have already referred. In 1931, as the result of certain evidence which seemed to point to a hydrogen isotope of mass 2, Urey and his collaborators undertook investigations which clearly established the existence of this second isotope, and soon after, by methods involving electrolysis—that is, the electrical decomposition of water—succeeded in preparing it in quantity. This isotope, then, possesses a nucleus having twice the mass of the proton. The heavy hydrogen has been given the special name deuterium and the nucleus is called the deuteron—sometimes the diplon, but the latter term is going out. The deuteron, then, has the same charge as the proton, but twice the mass. Urey received a Nobel Prize in 1934.

It must be realized that the amount of deuterium in ordinary hydrogen is very small, only about one part in five thousand. Nevertheless, tolerably pure heavy water, which is water containing deuterium in place of hydrogen, has been prepared in large quantities, mainly in Norway, where there is very cheap water power to generate the large amounts of electrical energy that are necessary for the electrolytic process in

use. Heavy water is nearly 11 per cent. denser than ordinary water, but has, of course, the same chemical properties. There is no truth in the rumour, current at one time, that it is a deadly poison. It has been drunk in relatively large quantities and it is hard to know how the story started. The deuteron has proved to be of great importance in atomic investigation.

To summarize, we may say that the atom has a very open structure consisting of a very minute massive nucleus, with a net positive charge, surrounded by a system of electrons circulating in orbits, or, on another view, by a complicated system of waves of a special kind, equivalent in most respects to such a system of electrons. The nucleus itself contains more units of mass than it does units of charge, which may be accounted for by saying that it consists of neutrons and protons, each of the latter having a unit mass and unit positive charge. The scale on which this system is built may be illustrated by reference to the atoms of an element about half-way on the list, as far as weight and complexity are concerned—namely, silver. There are two isotopes of silver, one with mass 107, and the other with mass 109 times that of the proton, while the number of units of net positive charge on the nucleus is 47. One isotope of silver therefore has 60 neutrons and 47 protons, while the other has 62 neutrons and 47 protons. The nucleus is about one two-million-millionth of an inch across; the nearest electrons, two of them, are at about a hundred times this distance from the nucleus. The outermost electron is ruling a shell of space which is, roughly speaking, about a hundred-millionth of an inch across. That is, if the nucleus be imagined to be about the size of a

billiard-ball, the distance of the nearest electrons will be somewhere about the distance from the centre of the table to the walls of the billiard-room, while the distance to the outside electrons will be about half a mile. In lighter atoms, the nearest electrons are somewhat more remote from the nucleus, but there are fewer electrons: in heavier atoms the nearest electrons are nearer to the nucleus, and there are more electrons in all. The examples quoted, however, will suffice to show how open is the structure of the atom.

An atom is empty space which has peculiar properties because of the presence of a few specks of electricity. The hardness of solids is due to the difficulty of forcing the atoms closer together, for the electrical forces of repulsion between the different atoms become very large when they are made to approach a little nearer to one another than their normal positions. These forces can, as a matter of fact, be calculated from the compressibility of crystals—that is, from the forces required to squeeze the crystal in by a given small amount.

We can now say a word as to one or two types of experiment by which this scheme of atomic structure has been established. If the structure of the atom is as loose as we have said, it should be possible for particles to pass right through it, if they are only small and swift enough. Now we know that the electron is very small, even compared to the size of an atom, and, by applying high voltages, electrons can be made to travel very swiftly in a cathode beam. Many years ago, Philipp Lenard, who was awarded a Nobel Prize for this work in 1905, observed that the cathode rays produced in an evacuated tube could be made to pass right through a

thin foil of aluminium or other metal, used as a window, out into the air, where, with the potentials that he used, they travelled an inch or so before being absorbed. He shows that the penetration obtained could only be explained if the swifter electrons could pass right through the atoms themselves which constituted the metal foil and the air molecules: the interspaces were not sufficient for the observed effect. This was the first proof of the emptiness of the atom.

There is, however, besides the electrons of the cathode beam, another class of very minute projectile at our disposal. The so-called radio-active substances give out of their own accord three different types of radiation, to which the names alpha, beta, and gamma rays have been given. The gamma rays we have already mentioned as a kind of very penetrating X-rays, a kind of wave analogous to light-waves, but of extremely short wave-length. The beta rays are very swift electrons, which the radio-active atoms shoot out spontaneously. The alpha rays are swift particles which turn out to be the nuclei of helium atoms—that is, nuclei of mass four and net positive charge two, the helium atoms being the next after hydrogen in order of atomic number. These alpha particles are fired out with a speed of some ten thousand miles a second, and so, in spite of their lightness, have a comparatively large energy. It must not be thought that all radio-active substances send out all three kinds of radiation, but rather that, when all the radio-active substances are considered, all these types of radiation will be found to be frequently represented. A particular radio-active element does not emit both alpha and beta particles. The velocity of the alpha particles is not the same for

all parent substances, but it is always in the neighbourhood of the figures cited.

These alpha particles have the very important property that, when they hit certain phosphorescent substances, they cause minute splashes of light, as it were, which can be seen through the microscope as tiny scintillations. When radium, the most famous of the radio-active substances, was first discovered, a little instrument called the spinthariscope aroused great interest. It consisted essentially of a screen prepared by covering a little plate with a phosphorescent substance, of a speck of a substance containing radium, and a lens to observe the little flashes on the screen. What was then little more than a toy was turned by Lord Rutherford, the head of the Cavendish Laboratory at Cambridge at the time of his death in 1937, into a very powerful weapon of research. For each tiny spark of light gives us the place where a single alpha particle hits the screen, just as the splash of a bullet in water would betray the arrival of the invisible bullet at the water surface. Hence we have a means of investigating what happens to alpha particles, although we cannot see them. We may speak of them as one speaks of a pushing individual, and say that they are so energetic that they make a splash.

Alpha particles pass through thin foils of metal to a degree that shows that they can penetrate right through individual atoms, and are not just passing between them. However, our little phosphorescent screen, together with a low power microscope to look at it, can be made to tell us something more about the passage—namely, how much different particles are turned aside in passing through the foil. We can control the

direction of the fine beam of alpha particles before it strikes the foil, so that we know the point of impact on the foil: the position of the scintillation tells us the direction of travel after leaving the foil. It is as if we were to fire bullets through a mud wall, say, detecting what happens to them by having a wood screen parallel to the wall, and observing by means of the flying splinters the place where the bullets struck the screen.

When such experiments were carried out, it was found that some of the alpha particles were turned aside through very large angles by passage through the foil. Rutherford showed that the proportion so turned aside could not be explained as a result of a lot of little deflections by different atoms, but must be due to something small, very heavy—compared to the electron—and with a large electric charge, existing among the atoms. From these experiments he deduced the nuclear structure of the atom. In our illustration of the mud wall, if we found that a fair number of bullets were deflected through very large angles in passing through the wall, we should deduce that the mud contained stones. By calculation the proportion of alpha particles turned through different angles may be made to tell us how heavy and how highly charged the mucleus is, and, in fact, such experiments on the scattering of alpha rays were originally our main source of knowledge about the nucleus.

Recently other methods of detecting single alpha particles have been devised, and the scintillation method, which is trying to the eyes and depends greatly on the skill and experience of the observer, has dropped out of use. The so-called Geiger-Müller counter, which is extensively used to register the passage of single

particles, is simple enough in principle. It is a development of a device originally used by Rutherford and Geiger and consists of a fine wire stretched along the axis of a metal cylinder containing a gas, say argon mixed with air. The wire is insulated and kept at a potential just not sufficient to cause a spark to pass. A swift particle creates electrified atoms and molecules along its path, as described in the next paragraph, and if this path passes near the wire these particles are driven along by the electric field, creating other electrified particles in their passage. The result is a momentary movement of electric charge, i.e. a very minute burst of electric current, which can be amplified by modern devices incorporating valves, of the type used on wireless receivers, until it is sufficient to cause a momentary deflection of a delicate instrument. This deflection can be photographed. By special valve circuits it is even possible to magnify the electrical effect until it is large enough to work a mechanical counter, which clicks over and shows a number. In this way the arrival of swift particles can be recorded. Counting devices of this type are extensively used to-day in all atomic research. In Fig. 8 are shown diagrams of two different types of counter. That above is for alpha or beta particles, which can enter through the very thin window at *a*. That below is for very penetrating units of radiation, such as those of cosmic rays.

Another weapon, of inestimable importance in atomic research, is the so-called "cloud chamber," invented by C. T. R. Wilson, who was awarded a Nobel Prize in 1927. By a very ingenious process the whole path of an alpha particle can be rendered visible, although each alpha particle is only the nucleus

of a comparatively light atom. An alpha particle flying through a gas passes through thousands of atoms, dislodging electrons from their outer parts, which electrons may then stick to other atoms, so that we have both positively and negatively charged atoms present all along its path. Now, if the air contains more than

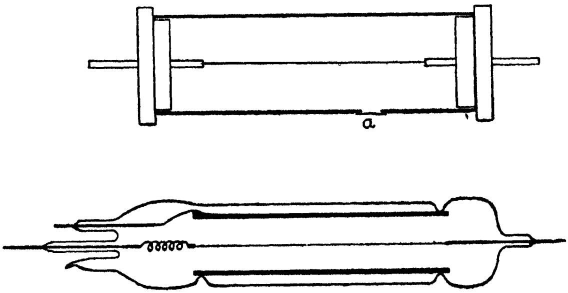


Fig. 8. Geiger-Müller counters.

a certain amount of moisture in the form of invisible vapour, the moisture will condense into tiny drops if it only has something to give it a start, to form a beginning of a drop, just as a cork may form the beginning of a ball of wool. A speck of dust will serve the purpose, but so will a charged atom, or even an electron, and this fact has an important bearing upon the rainfall, which cannot be considered here. For our present purpose, what is important is that the alpha particle in its passage creates a number of charged atoms on which, in special circumstances, moisture can condense in minute drops. Other swift particles, such as electrons, produce similar effects.

If now the particle be traversing moist air, and the air be suddenly cooled so that the moisture wants to settle, a number of tiny drops will be formed, one on

each electrified particle, and these drops will define the path of the particle in a visible way. The drops are so small and so close that, with suitable illumination, the path of the particle appears as a clearly defined white line. It is as if a bullet were fired through a cornfield and a flock of pigeons promptly settled on the broken ears, defining the invisible path of the bullet. The line of pigeons would not appear, of course, until long after the bullet had passed, and in the same way the line of droplets does not appear until after an interval which is long compared to the time that it takes the particle to cross the vessel.

The devices by which the experiment is made to work successfully are extremely ingenious. The sudden cooling of the moist air is produced by a slight expansion of the air: for, just as compression of air produces heating, as may be noted in pumping up a tyre, expansion leads to instantaneous cooling. The paths are photographed by a momentary flash of light.

A modern form of C. T. R. Wilson's cloud chamber is shown diagrammatically in Fig. 9. C is the glass chamber, in which the air is kept moist by a layer of wet gelatine which covers part of the surface. The floor A of the chamber, shown black, is attached by a ring of rubber, shown white, to the metal wall: it can be made to descend suddenly, and so cause the air in the chamber to expand, by abruptly lowering the pressure of the air beneath it, through the tube R_2. At G is a stop, to control the amount of movement of A, and thus produced the desired expansion of the air in C. There is a light-source beyond the lens O to give the illumination necessary if the ray tracks are to be photographed by the two cameras P_1 and P_2.

If the tracks were photographed from one direction only it would not be possible to determine, for instance, the angle between the two branches of a forked track or the curvature of a curved track, since what is

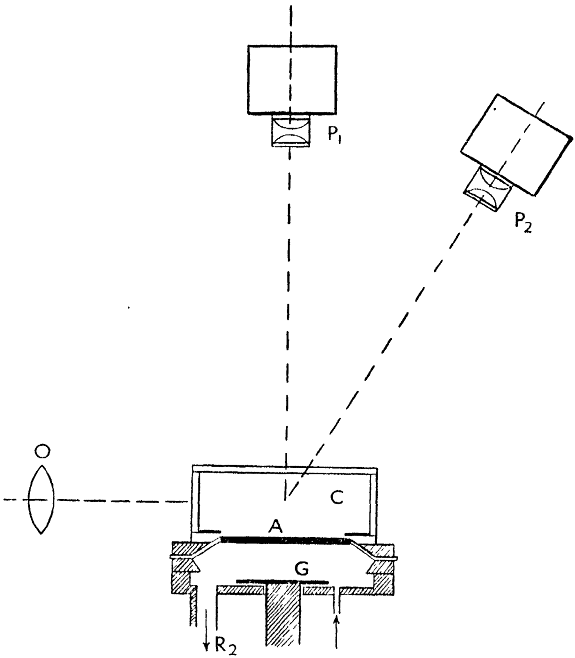


Fig. 9. A modern form of Wilson cloud chamber (adapted from Leprince-Ringuet's *Les Rayons Cosmiques*).

obtained on the plate depends on the angle of view. Two photographs from different angles, however, enable the tracks in space to be worked out.

Plate VI*a* shows an early cloud chamber used by Wilson himself. The fall of the black piston, seen

inside the chamber, is produced by the sudden expansion of the air beneath it into the glass flask seen on the right.

The picture of the tracks of electron and positron given in Plate II*b* is a good example of a modern Wilson cloud chamber picture, in which the individual water-droplets can be seen. The discovery of the positron was, in fact, due entirely to the cloud chamber. Further examples of cloud chamber photographs will be found later in the book.

VI

HOW THE ATOM SENDS OUT LIGHT

Are not gross Bodies and Light convertible into one another, and may not Bodies receive much of their Activity from the Particles of Light which enter into their Composition?

I. NEWTON. *Opticks*. Second Edition. 1717

An intelligent student, armed with the calculus and the spectroscope, can hardly fail to discover some important fact about the internal constitution of a molecule.[1]

J. CLERK MAXWELL. Lecture delivered to the Chemical Society in 1875

We know that the atom, when suitably stirred up (or excited, to use the scientific term), can give out electromagnetic waves which are called infra-red, visible light, ultra-violet, or X-rays, according to their wave-length. We have first of all to discuss in a little more detail the nature of these radiations, and then to inquire as to the machinery by which the atom sends them out.

To examine the different wave-lengths which a source of light is emitting we have to resort to an instrument. When a chord is struck on a piano, a trained musical ear can tell at once what separate notes are in the chord, but when we are dealing with a light that contains several different distinct wave-lengths, such as a certain definite green light, a certain definite yellow light, and a certain definite red light, each of a

[1] Clerk Maxwell often used the word "molecule" where we should say "atom."

given wave-length (a chord of colour, we may call it), no eye can say what these different colours are which exist together in the light. For instance, a white light can be made by mixing three different coloured lights in due proportion, which is even to the trained eye indistinguishable from a white light made by mixing four different coloured lights, or by mixing all the different colours of the spectrum in the right proportions. The way to analyse the light from a given source is to use an instrument which separates out the different wave lengths and sorts each into a different place.

To get a rough illustration of what is meant, suppose the tickets to the different parts of a theatre were printed in different colours, as red for the pit, orange for the stalls, blue for the dress circle, and so on. Outside the theatre we have a mixed crowd passing in, corresponding to the beam of mixed light, but inside the various colours are sorted out, and we know by the position in which people sit down what colour their tickets were. A sorting-out instrument for light is called a spectroscope, or, if it is suitable for photographic recording, a spectrograph. The light which enters is spread out into a band, in which each wave-length has its own position, and even a colour-blind man can tell the colours present in the beam by the places in which light appears.

The spectroscope is much more sensitive than any eye to differences of shade. Lights of several near wave-lengths all appear to the eye to be of the same hue, say a particular shade of red, even when they have each been put into its proper place. The fact that after passing through the spectroscope they fall into different places near one another tells us, however, that

the wave-lengths are actually somewhat different. If all kinds of light are present (all hues, that is) the spectroscope shows us a continuous band of colour, ranging from red, through orange, yellow, green, blue, and indigo, to violet. There are no gaps in the band. Most people know that sunlight is spread out into such a continuous band[1] by a prism. This was Newton's famous experiment, which led to the discovery that the white light of the sun contained the various colours. The band is known as a spectrum. A continuous spectrum corresponds in music to all the notes being sounded at once: not to a piano having all its notes depressed at once, for the notes in a piano have intervals, tones and semitones, between them, but rather to a violin string being bowed while the finger is slid along the string, without a break, producing a whole range of tones blending into one another. Some spectrographs contain prisms to split up the light; others make use of other devices.

Suppose, however, that we examine, not the light from a glowing solid, but from a glowing gas, say from one of those tubes, filled with the gas neon, which give a reddish glow when an electric current is passed through them, and which have been so much used for advertising signs at night. We no longer find a continuous band, but certain bright lines separated by dark gaps. The dark gaps mean that the light passing into the spectroscope from the tube contains no wave-lengths which belong to the places where there is darkness: the light contains, rather, only certain definite wave-lengths corresponding to the positions of the bright

[1] Except for certain narrow black lines which need not trouble us here, great as is their importance for certain considerations.

lines. We may see red lines, and blue lines, but the exact position of the lines tells us the exact wave-length, while the colour of the lines only tells us roughly in what region of wave-lengths the lines lie.

The fact that we see *lines* is due to the fact that the light enters the instrument through a narrow slit: the lines are images of the slit. If the light entered through a round hole we should see little discs of different coloured light, separated by darkness. The use of a slit is clearly better for accurate measurement, and prevents overlapping. A spectrum which consists of bright lines with darkness between them is called a line spectrum, and clearly corresponds to a chord of colour, in which certain definite notes—wave-lengths—alone are present. Not only visible light, but also infra-red and ultra-violet lines can be measured with the spectroscope: the former are detected by a delicate electrical instrument which measures the heat they produce, while the latter affect a photographic plate. Most modern investigations of spectra, except in the far infra-red, are made by photography: the spectrum appears as lines in the photographic plate, and the measurement of the position of these lines gives their wave-length.

Hot solids give a continuous spectrum. In a solid all the atoms are very near to one another, and are always influencing one another—that is, preventing one another from singing clearly the notes to which they are naturally inclined, as it were. In a gas, especially a gas at low pressure, the atoms are far apart, and, except for occasional collisions, can behave as if they were alone. Clearly, then, if we want to study

the kinds of light peculiar to atoms we should examine the line spectrum of a gas.

The atoms can be made to give out light in various ways. We can shut up the gas in a tube, and pass an electric current through it. We can produce an electric spark or an electric arc. Some of the material of the metals between which the arc or spark passes is vaporized, or turned into gas, by the intense heat, and we get the line spectrum of the kind of metal in question. We can also vaporize metals in flames, and get their spectra in this way. For instance, if a little common salt is brought on a clean platinum wire into a colourless gas flame, such as burns on a gas stove, the flame turns yellow, owing to the fact that the sodium atoms in the salt are giving out a line spectrum in which the strong visible line is a yellow line. Different ways of stirring up the atom can make it give different spectra, but, in general, not more than two different spectra. We can roughly illustrate this by pointing out that an organ pipe will give a different note according as to whether it is blown violently or softly. The point which must be grasped is, that if we knock the atoms of a gas about by electrical means, or by heat, we can make them give out characteristic cries of light, as it were, which give us a definite information as to the way in which they are built.

We can make our problem clearer by considering the atom as a musical instrument, say, a piano, draped round with curtains so as to be invisible. We must suppose ourselves to be in the position of a man who has no idea what a piano is like, and who cannot raise the curtains. He can fire bullets through the curtains, and may judge from the fact that they are deflected

that within the curtains is something solid. This corresponds roughly to the experiments with alpha particles which reveal the nuclear structure. Occasionally he may knock off a bit of the piano, which is thrown through the curtains. This corresponds roughly to the way in which bits—protons—are knocked off the nucleus, as described in the next chapter. Further, he can shake the piano about by tampering with part of the floor, throwing bricks at it, or even throwing another piano at it, and judge from the chance notes produced that the piano contains wires strung in certain ways. This corresponds to out experiments on spectra. The idea which the investigator employing these means may form of the piano may not be quite right, but he might find out that it contains wood, ivory, and wires, and if he was clever, that striking the ivory causes a wire to sound. The illustration is, of course, only very rough, as all such illustrations must be, but it may give some conception of the nature of the problem, and of its difficulty.

Before considering how the visible and ultra-violet lines are produced, we must mention that the X-radiations can also be split up into a spectrum, by the use of crystals disposed in certain ways. This was first demonstrated by the German physicist Laue, who was awarded a Nobel Prize in 1914, and the method was turned to magnificent account by Sir William Bragg, and his son, W. L. Bragg, now Sir Lawrence, who obtained a Nobel Prize jointly in 1915. The X-ray spectrum of a given kind of atom consists of certain distinct wave-lengths, or X-ray lines. We know that X-rays are produced by letting the cathode

rays, which are very swift electrons, fall on a solid, which in the ordinary X-ray tubes is a lump of metal. The X-ray spectrum produced will largely depend upon the kind of metal employed. The swift electrons pass right through the atoms, as we have learnt, so that when we produce X-rays we are not just banging about the outsides of the atoms, but stirring up their insides, parts nearer the nucleus. Since only the outside electrons of an atom are disturbed by the proximity of another atom, or by chemical combination, an element in the solid state gives the same X-ray line spectrum as the same element in gaseous form, so that the X-ray spectrum is not affected, like the optical spectrum, by chemical combination.

The same atom, then, can give out one or more optical spectra, each consisting of a different arrangement of lines, or it can give out an X-ray spectrum, the particular radiations which it emits being decided by the way in which we knock it about. The comparatively mild disturbance produced by the flame or the electric arc gives one type of optical spectrum: the more violent disturbance produced by the electric spark gives a different arrangement of lines, but still an optical spectrum: the keen thrusts of the swift electrons into the interior of the atom produces an X-ray spectrum. We can now turn to the problem of how and why a given kind of atom sings, as it were, two characteristic songs in the middle register, and others in a very high soprano.

We know that the atom can be considered as consisting of a nucleus, round which electrons run their courses in orbits. We have already referred to the

fact that this picture has been superseded by the somewhat different conception offered by wave mechanics, but the orbital scheme is simpler to understand and we will adopt it for the moment, reserving a few words on the more modern representations until later. Considering the orbits, then, we can divide the electrons into groups, of which we can say that, speaking roughly for general purposes, one group consists of electrons whose paths lie comparatively near the nucleus, a second group of electrons whose paths are somewhat farther from the nucleus, and so on, until we come to the outside group, the number of groups depending on the number of electrons in the atom. The heavy atoms, with the most electrons, have the largest number of groups. To illustrate this, we give the orbital schemes for an undisturbed atom of neon, which is chemically neutral and has a very closed structure: an undisturbed atom of sodium, which has one "outside" or privileged electron: and an undisturbed atom of copper, which is much heavier, but likewise has one "outside" electron (Fig. 10.) The atomic numbers of these elements are, respecively, 10, 11 and 29.

It is an essential feature of the modern theory of the atom, which finds its equivalent representations in all theories, that each electron has a definite orbit or energy level, to which it sticks unless it is subjected to particularly rough treatment. Let us consider first the outside electrons. It might be supposed that if an outside electron were disturbed by a knock of any kind, it might leave its orbit, and stumble into one very near it. This, however, we find not to be the case. If it is disturbed, it either takes no notice or else leaves its

orbit altogether, and goes to quite a different one a good deal outside the atom. It has a certain choice of orbits to which to go, but it has not a choice of all the orbits which are mechanically possible on the classical theory of the motion of a particle.

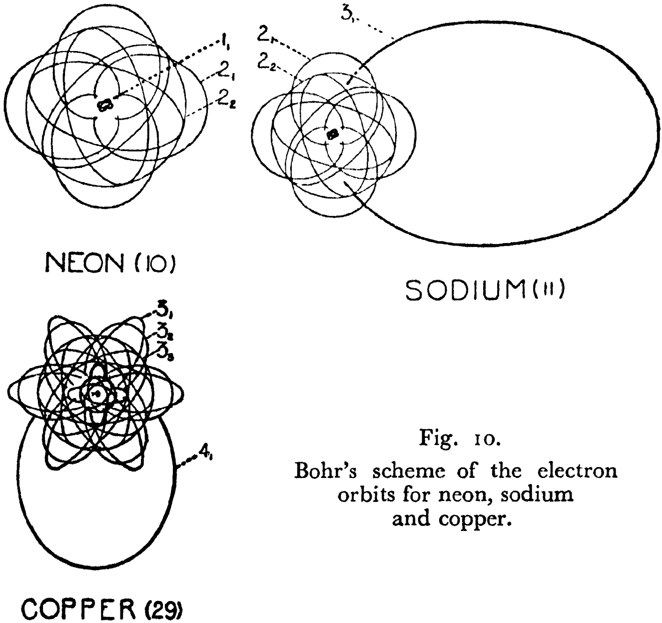


Fig. 10.
Bohr's scheme of the electron orbits for neon, sodium and copper.

To illustrate this we may consider a ball lying at the bottom of a flight of steps. If it is thrown from its position, it may settle on any one of the steps, but cannot decide on a position between the steps. Thus it may, if the steps are one foot high, be thrown into a position one, two, three, or more exact feet from the ground; but it cannot be placed one foot ten inches from the ground, in whatever way we throw it, although

there is no law in nature that says a ball may not, in certain circumstances, be placed one foot ten inches from the ground. Similarly, we cannot throw the outside electron into any orbit we like, but only into certain orbits determined by mathematical conditions. When we throw the electron into such an orbit the energy of the atom is different from its normal value, and we can express what we have said by saying that the atom can exist in certain so-called stationary states, of fixed energies, but cannot exist in states of intermediate energies. Our ball cannot hang in the air. The term "stationary" does not refer to the electron, which is moving, but to the fact that the state is a steady one, in which an atom can exist for a finite time.

Another way of illustrating this fact that an atom can exist in certain stationary states is to suppose a circular board prepared so that the surface slopes gently from the centre, and to have shallow circular grooves, surrounding the centre, cut in it. A ball will then be able to execute certain circular motions—namely, those for which grooves are provided, but will not be able to run round in any intermediate position. On the orbital theory the space round the nucleus behaves as if there were grooves in space in which the electrons can run, so that if one be taken out of one groove it has to settle down in another. On the theory of wave mechanics the space round the nucleus behaves as if it could vibrate, but in certain patterns only. Why the atom has these stationary states of energy, and cannot have intermediate states, we cannot readily explain: the theory of wave mechanics gives a more consistent picture of the fact, but still leaves it

as a fundamental fact of Nature. All recent experiments confirm us in our belief that it does behave in this way.

Suppose, then, that we hit an atom, either with a swift electron, or with another atom moving at comparatively high speed (such as that possessed by atoms in a very hot furnace), or that we expose it to an electromagnetic wave of high frequency, we may shake one of the outside electrons into a new orbit, and the whole atom will at once settle into a state in which it has more energy than it normally has. The atom when in this state is said to be excited: we might more colloquially say that it is wound up. We have put energy into it, and that energy is temporarily stored. The atom, however, will have an opportunity to return to its normal energy state, and after a short interval will do so. Alternatively it may pass to a stationary state of less energy which is, however, not the normal state, and afterwards pass to the normal state—that is, it may return to the normal state in two jumps, instead of all in one jump. When the atom does return to its normal state, it gives out energy—namely, the energy which we put in when we excited it. This energy is given out as radiation, and the wave-length of the radiation is determined by the amount of energy given out. We will now briefly consider the law which is obeyed.

When we were discussing the quantum, or atom of radiant energy, we mentioned that it was obtained by multiplying the frequency by a certain fixed number, called Planck's constant, always denoted by the letter h. When the atom changes from one stationary state to another, it gives out one quantum, one

unit amount, of radiant energy. According to the kind of atom—that is, according to the nuclear charge and the distribution of the other electrons—and to the particular stationary state from which the atom passes to some other stationary state, the amount of energy given out may have very different values, so that, if in all cases it is one quantum, the frequency ν must also have different values.[1] We may write:

$$E_1 - E_2 = h\nu,$$

or in words—

> Energy in higher stationary state minus energy in lower stationary state equals Planck's constant multiplied by frequency.

The value of Planck's constant is known from many different types of experiment: it is a number fixed once for all, like the velocity of light, a so-called universal constant. Therefore, if we know the energy of the atom in the initial and in the final stationary state, we can very easily find the frequency of the radiation given out. The frequency tells us the wave-length. For the frequency is the number of complete waves given out in one second, so that the frequency multiplied by the wave-length must be the distance travelled by the waves in one second—that is, the velocity of light, which we know. Hence, if the atom is put in a stationary state which has a great deal of energy, and passes to a stationary state which has little energy, it gives out a high frequency radiation—that is, a radiation of short wave-lengths. Conversely, if the energy change is but small the radiation given out has a long wave-length.

[1] ν is the Greek letter *nu*, always used to denote atomic frequencies.

There are various types of stationary state permitted in any particular atom, with each of which a certain energy is associated. They are governed by certain mathematical rules which have been worked out for what is, in a sense, a new astronomy—namely, the astronomy of the infinitely little. In the case of the astronomy of the heavenly bodies, we can observe the planets directly, map their motions, and work out a dynamical theory, based on Newton's laws, which enables us to account for their behaviour, and predict their future motions. In the case of the astronomy of the atom, where we are studying the motions of electrons round the nuclear sun, we cannot use the microscope to take the place of the telescope, for the planetary system in question is much too small for the microscope to be any good. Instead, we observe the radiations, which really tell us about energy states and not about orbits. The fact that we can never hope to observe the electrons directly is another reason which has furthered the adoption of the alternative scheme of wave-mechanics.

A particular sort of atom, say, the sodium atom, gives out certain definite wave-lengths only, each one corresponding to a line in the spectrum which characterizes sodium, and these wave-lengths can be sorted out and arranged in certain series. From the general laws which we have just mentioned the energies of the atom in its different stationary states can be worked out, and from these stationary states the laws which the mechanics of the atom must obey can be deduced. Of course, what we observe is the result of millions of millions of atoms undergoing changes. Each atom only gives out one wave-length at a time; but at one

time it gives out one wave-length, at another time, by a different permitted change, another wave-length, so that when we observe the radiation from the whole gas we get a sample of every possible radiation which the atom can produce under the given conditions.

This conception of the way in which light is emitted is known as the quantum theory of spectra, and was first put forward by Professor Bohr, the great Danish physicist, who was awarded a Nobel Prize in 1922. It is all very mysterious, even to the experts. It is difficult to understand why the atom exists in these states separated by finite steps of energy—that is, why it is wound up as if controlled by a toothed wheel and ratchet rather than as if controlled by some kind of friction grip, which would stop it at any stage. The wave-mechanical scheme does, it is true, give a mathematically and physically consistent picture of the stationary states, but it is based on an equation which is hard—one might even say impossible—to explain in terms of the ordinary conception of physics, although it may be illustrated by analogies. No one knows why the radiant energy is given out in quanta, whose frequency is determined by the energy. We only know that all the evidence indicates that things are so. The radiant energy is given out in jerks, and not in a steady supply. The atomic, or granular, nature of things seems to prevail, as against the non-atomic, or continuous nature, wherever we turn in our quest for fundamental facts.

If an atom be struck hard enough by an electron, it may lose one of its own electrons completely, and so acquire a positive charge as a whole. After existing for a time as a structure which is short of one electron.

it may capture some electron which happens to come near, for in a gas which is sending out light there are always plenty of electrons about. The electron will go to one of the selected orbits, and the atom will give out a radiation of wave-length fixed by the change of energy. But it may happen that before the atom has regained the electron which it lost, a second electron is knocked from its normal orbit into another permitted orbit, and that later the two displaced electrons are replaced either one by one, or, occasionally, both at once. An atom which has already lost one electron has quite a different series of possible states of stationary energy from an atom which has all its electrons. This accounts for the fact that one kind of atom may give two different spectra, or, as we have put it, can sing two different songs. It is a pretty experiment to pass a mild electric discharge through a gas in a tube, and produce a light of one colour, and then by increasing the violence of the discharge, produce a light of another colour. Of course, in both cases the light consists of a whole range of different colours mixed together. We have what we have called two different chords of colour.

We have spoken of two different spectra, which are all that is usually observed, but it has proved possible in the case of certain atoms to knock two outer electrons off, and to obtain another spectrum corresponding to shifts of an outer electron in the mutilated atom, already short of two electrons. This gives a third spectrum, and even further spectra have been obtained in special cases. There is nothing surprising about this: an atom which has lost an electron, or a number of electrons, clearly has, for the time being, a different set

of electrical forces prevailing within it, which mean a set of stationary states and a spectrum different from those of the neutral atom.

So far we have spoken of hitting the atom hard enough to displace one or two outside electrons. Suppose, however, we bombard the atom with very swift electrons, as we do in an X-ray tube, where we use large electric forces (very high potentials) to hurl the electrons against the metal lump which is called the anti-cathode. The shock is then violent enough to throw an inside electron out of the atom, which requires a comparatively large amount of energy. An orbit which is possible is then left vacant *in the interior of the atom*: the atom is in an excited state. Now this orbit can be filled by an electron passing to it from one of the other occupied orbits in the interior of the atom. When this change takes place there is a large change in the energy of the atom, and we have a radiation of very high frequency produced—namely, a penetrating radiation which we call an X-ray. Of course, the orbit vacated by the electron is subsequently filled by an electron from another orbit, until finally an electron from outside the atom comes in to complete the structure again. We thus have X-ray lines produced. The frequency of the radiation depends on the orbits between which the electron is interchanged.

There is a central nucleus and round this is the distribution of negative electrons which we have visualized by imagining electrons running in certain fixed orbits. We can, if we like, imagine the electrons as beads running on wires: in that case there will be a large number of separate wires bent into curves surrounding the nucleus, such as are shown in Fig. 10.

This represents the state of affairs in a neutral undisturbed atom. There is, however, in addition a complicated series of vacant wires which lie, in the main, outside these occupied wires and represent possible temporary paths for electrons if the atom is disturbed. When we disturb the atom by a strong enough electric shock, one of the outside electrons will leave its wire and pass to one of the unoccupied wires farther out, and run on it. We must suppose that this takes place very quickly in a way not understood, so that just before the shock we have one arrangement, just after the shock the other arrangement. Later, the electron goes back in a flash to an unoccupied wire nearer the atom. At the same time a little parcel of radiant energy is sent out, of a wave-length which depends upon the two wires concerned in the change. If we hit the atom still harder, one of the inside electrons leaves its wire. It cannot pass to one of the near wires, since they each have an electron already, but will pass to an unoccupied wire just as the outside electron did. Some other electron will then leave its wire, and pass to the unoccupied wire, and we have an X-ray, of frequency corresponding to the energy change. The place of the last electron is taken by another electron, and we have another X-ray, of different frequency, and so on, until the atom is in its normal state again. Speaking very generally, we may say that the negative electricity surrounding the nucleus conforms to certain prescribed patterns, and that when the atom passes from one pattern to another, radiation of some kind is given out. If we put it as generally as this, our description will cover the wave-mechanical scheme as well.

An atom is, then, a minute broadcasting station, and to each kind of atom certain wave-lengths are allotted. Thus Europe, whose broadcasting stations, taken all together, would give a certain selection of wave-lengths, might be fancifully supposed to represent an atom with a given spectrum. America, which sends out a different set of wave-lengths, would represent another kind of atom, with a different spectrum. By studying the wave-lengths an expert would tell us the kind of electrical system which each continent contains, and similarly by studying the wave-lengths, the physicist tells us the kind of electrical system which each atom contains. In the case of both broadcasting stations and atom, everything reduces to a motion of electricity.

In conclusion, a word must be said about the application of what is called wave mechanics to the electronic part of the atom. The Bohr theory of electronic orbits was able, with its various elaborations, to account for all the main features of the often very complicated spectra of the different atoms, but, fundamental as were its services to atomic science, it presented certain defects from the point of view of logical consistency. On the standard theory of electromagnetism, electrons circulating in orbits must radiate while they are doing so, but Bohr had to assume that in the atom they could go round and round the nucleus, in his "stationary" orbits, without radiating. He had to lay this down, without explanation. Again, his rule giving the frequency of the radiation, while leading to very satisfactory results, has no real theoretical justification. It has also been objected that the scheme is unsatisfactory because not only have the orbits never been

observed but because it is not only practically, but fundamentally, impossible to observe them, for the following reason. In order to fix the position of any particle it is necessary to make it send out some kind of signal which can be detected somehow or other. By our very assumptions the circulating electron does not send out any kind of radiation, so that we must illuminate it in some way. If, however, a quantum of light or any kind of radiation falls on an electron it affects it in the same way as would the impact of a particle—it drives it from its place. In the very process of trying to find out where it is, then, we shall push it to somewhere else and, for certain fundamental reasons, it is impossible for us to gain sufficient information to work back and find where it was before it was pushed. The situation reminds us of G. K. Chesterton's old argument that there could never be a completely realistic play, because, however naturally the people on the stage might seem to be behaving, nobody would really behave like that if the fourth wall of the room were taken away and a theatre full of people substituted for it. The mere fact that they were observed would make the behaviour of the actors unreal: it would only be natural if there were none there to see it. In the same way, any attempt to find out where an electron is at any particular instant is doomed to failure, because the act of observation puts it somewhere else to an unpredictable extent.

Heisenberg, in fact, has shown on fundamental grounds that it must be impossible to determine both the position and the velocity of an electron at the same time; the more certain we become of one, the vaguer we are as to the other. This, more precisely

formulated, is what is known as Heisenberg's uncertainty principle. It is of some philosophical importance, because it used to be believed that if we knew—which, of course, we could never in practice know—the position and velocity of every particle in the universe at a particular instant, it would, in principle, be possible to work out the whole future history of the universe. All subsequent happenings would be at any instant effectively fixed by a specification at one particular moment of the positions and velocities of every material particle in the universe, including all the atoms and their parts which constitute the human frame. We now believe that it is basically, and not just practically, impossible to know both the position and the velocity of any fundamental particle. For some minds this restores free will to the world, but for others free will is independent of theories designed to explain the behaviour of ponderable matter. The behaviour of atoms in a vacuum tube is complicated enough, Heaven knows, but the secrets of the soul may be even harder to win, and may need other methods.

From the point of view of wave-mechanics we do not pretend to know where each electron is and how it is moving, as we did in the orbital scheme. What we deal with are mathematical expressions which tell us what is the chance, the probability, that at any moment there will be an electron in any particular little volume. Thus, on the old point of view, we had a path for the electron and a time table, which told us where in the path it would be at any instant. On the new point of view we have places where there is a good chance, on the whole, of finding an electron and places where there is a poor chance; with every

spot is associated a certain probability. Another way of looking at it is to suppose the electrons smeared out, thick here, thin there, but although this comes to the same thing mathematically it is not very easy for a physicist to think of a squashed electron. We can, however, talk of an electronic cloud: when the cloud is thick it means that there is, on the average, a good chance of finding an electron, and when the cloud is thin there is a poor chance.

The pictures of Plate IV represent the forms of the electronic cloud distributions that belong to certain of the various possible "excited" states of the simplest atom, the hydrogen atom with its one electron. In each case, in order to get the distribution in space, we must imagine the pattern rotated round an axis running through the middle of it and parallel to the long edge of the paper. On the older form of theory we should have pictures of electron orbits to represent these excited states and they would be circular in all the cases represented except (*k*) and (*l*), in which cases they would be elliptical. In general, when there are more electrons, the cloud forms cannot be so simply represented and no attempt is made to draw them: the results are obtained from mathematical formulae without any attempt at pictorial representation.

The mathematical equations that express the state of the electronic part of the atom resemble in some ways those that govern the vibrations of a thin metal plate. Consider a round plate fixed firmly at the edge, like the diaphragm in a telephone receiver. It may be made to vibrate steadily in various possible ways, of which a few of the simplest are expressed in Fig. 11. The sign + indicates that the part so marked is up for

the moment, while - indicates that it is down. Half a period of vibration later, of course, that +'s will be down, and the -'s up. At (*a*) we have the plate swinging up and down as a whole, as indicated at the top of the diagram. In the mode of vibration represented at (*b*) there is a circle—a so-called nodal circle—

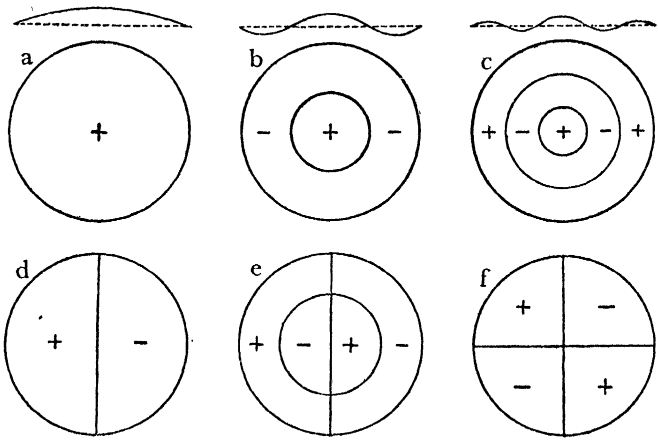


Fig. 11. Some of the modes of vibration of a circular plate.

which remains at rest, the centre of the plate swinging up and down, and the ring outside the nodal circle swinging down and up, as indicated. In the mode represented at (*c*) there are two nodal circles besides the outside one: the plate at the centre and between the two outer circles being up when it is down between the two inner circles, and *vice versa*. At (*d*) the plate vibrates with a diameter at rest, the two halves to either side going up and down in exact opposition. The modes of vibration represented at (*e*) and (*f*) should be clear. To each mode of vibration corresponds a particular frequency, which, if the plate were vibrating

in air, would mean a particular note would be heard, different in each of the six cases illustrated, and in the multitude of other possible modes of vibration not illustrated. The plate must take up one or other of certain fixed modes of vibration, each characterized by a particular frequency: it cannot adapt itself to vibrate with any frequency in between.

The case of the atom is much more complicated, for not only is it hard to explain what is vibrating but also, instead of a flat surface (i.e. two dimensions) we are dealing with ordinary spaces, with three dimensions. However, the point is that the vibrations divide the space up in different ways, and that, whatever it is that is vibrating, we can from it deduce mathematically the way in which the electronic charge is, on the whole, distributed, or, on the other view, the chance of finding an electron at every spot. Essential for our purpose is the fact that we can calculate the energy corresponding to each possible state, which gives us the frequency of the radiations emitted. The mathematician is content with symbols that express vibration, without needing to inquire too closely as to the physical nature of the vibrations, just as the ordinary citizen is content with the fact that his symbol, the pound note, will buy something without, perhaps luckily, inquiring too closely as to just what it represents.

VII

THE TRANSMUTATION OF THE ATOM

The changing of Bodies into Light, and Light into Bodies, is very conformable to the Course of Nature, which seems delighted with Transmutations.

I. NEWTON. *Opticks*. Second Edition. 1717

On this view, the radioactive substances are undergoing spontaneous transformation with the appearance of a number of new kinds of matter which are unstable and have a limited life. The radiations accompany the transformations and are produced as a result of an explosive disturbance within the atom.

RUTHERFORD. *Radioactive Transformations*. 1906

Il y a plus, et dans ce noyau atomique si prodigieusement petit, on peut déjà entrevoir un monde infiniment complexe.[1]

JEAN PERRIN. *Les Atomes*. 1913

WE have now discussed the way in which the old conception of the atom as a hard structureless unit has been replaced by the modern picture of the atom as a very open structure, consisting of a compact nucleus, made up of protons and neutrons, surrounded by a sparse assembly of electrons obeying very complicated laws, unlike those of ordinary mechanics and electricity. We have briefly considered the emission and absorption of electromagnetic radiation by the electronic part of the atom in the light of these laws. There is another fundamental respect, however, in which our modern

[1] "Further, in this atomic nucleus which is so prodigiously little, we can already glimpse a world that is infinitely complex."

knowledge of the atom has proved the old conceptions to be wrong. Up to the end of the last century it was firmly believed that it was impossible by any agency to break, damage, divide or change an atom. Nowadays we know, on the contrary, that atoms can be broken, changed, transformed in the laboratory and that certain classes of atoms, the so-called natural radioactive elements, change their nature spontaneously. This means that the nucleus, the ruler of the atom, is susceptible to change. We have now to consider the discoveries that established this fundamental fact.

As, however, we shall be frequently speaking of energy it may be well to insert here a brief digression on what we mean by the term. Energy is the capability of doing work, and by work we mean, in science, making a body move against the action of some force. Thus, when we lift a weight we do work against the force of gravity: when we turn the armature of a dynamo, supplying current to lamps or machines in a closed circuit, we do work against electromagnetic forces—and partly against frictional forces, which are always present in machines: when we drive a ship through the sea we do work against the resistance which the water opposes, in complicated ways, to the movement of any body through it. When, however, we press hard against a wall, although it may make us very tired, we do no work against the wall, since it does not move. Power, which is sometimes confused in popular talk with energy, is the rate of doing work, or in other words, the work done in unit time. Thus, a horse power is the work required to lift against gravity thirty-three thousand pounds vertically through 1 foot, or 1 pound through thirty-three thousand feet,

delivered every minute. The engineer says that one horse-power is 33,000 foot-pounds per minute. A kilowatt is another unit of power, defined in terms of the gram, centimeter and second instead of in terms of the pound, foot and minute.[1]

The basis of our whole modern industry is the search for convenient sources of energy, or power, if you prefer it, since the energy must be delivered in a reasonable time. Nature offers us certain obvious drivers of our machines, which have been used for centuries, and are being exploited more scientifically to-day. The winds and waterfalls consist of matter which nature has put in motion for us, and the wind-mill and the water-wheel were early invented to turn part of this energy of motion to the working of machines for grinding corn and performing other mechanical tasks. In these cases we do not have to consider atomic processes: the masses move as a whole, and whether the air and the water consist of atoms or not does not matter for the purpose in hand.

We may note, however, that the energy of both winds and waterfalls is ultimately due to the sun's energy, for the winds are caused by unequal heating of the earth's surface and it is the sun's heat that evaporates the oceans and so supplies most of the water vapour for the clouds whose rain feeds our rivers. The sun's heat, as we shall see later, is maintained at the expense of atomic energy, so that, in the end, we are brought back to atomic questions, even if we can calculate the dynamics of a water wheel without considering atoms.

The other great source of energy which we employ

[1] One kilowatt is equivalent to about 1·34 horse power.

to-day is combustion. In the steam-engine we burn coal or oil, producing heat, which is a form of energy, and it is the task of the engineer to convert this heat energy into work, in which task he is guided by the science of thermodynamics. In internal combustion engines we likewise burn fuel, petrol or oil, although under somewhat different conditions, for the combustion takes place in the cylinder, and not under a separate boiler, and once more thermodynamical considerations govern the design of the machine which is to convert heat energy into ordered mechanical motion. The ultimate scientific question is, however, as to how this heat energy is liberated by combustion, and here we have an atomic question. The law of the conservation of energy tells us that energy cannot be produced, but only converted from one form to another. In the case of the water-turbine, part of the energy of motion of the water is converted into the energy which the machine applies to its task: the water enters with a high velocity, and is discharged with a low velocity. In the case of combustion, the products of combustion, which are the gases which issue from the machine (and, in the case of the coal-burning furnace, the solid ashes which remain behind), must contain less energy than the original matter which takes part in the combustion —namely, the fuel and the air of the atmosphere. The vapour and air enter the internal combustion engine, and different gaseous substances are discharged through the exhaust. We have to inquire what the atomic theory tells us of the transformation which has taken place.

The energy of an atom depends partly, as we have seen, on the particular arrangement of the electrons. If we can modify their distribution, we change the

energy. Now, when chemical combination takes place between two single atoms, to take the simplest case, the behaviour of the outside electrons of each atom must be modified in such a way that the two atoms no longer have an independent existence, but are bound together and behave as a whole. In the commonest type of chemical combinations the atoms have two electrons in common—that is, which form part of the structure of each of them in turn. There is a perpetual exchange of the two electrons between the atoms, the quantum theory of which has been worked out on the basis of wave-mechanics. We say that the atoms are held together by "exchange forces." The energy of the two-atom system is different from the sum of the energies of the two atoms when separated. This combination of two atoms is, of course, a very simple molecule, but similar considerations hold for more complicated molecules. There is also a type of chemical combination in which one atom gives an electron permanently to the other, so that we then have one atom with a positive charge, and the other with a negative charge, and they are held together by ordinary electrical attraction. Such a case is sodium chloride, common salt, the crystal of which consists of alternate sodium and chlorine molecules regularly arranged. Here again there is a change of energy on combination.

The intrinsic or internal energy of the molecule is in general, but by no means always, less than that of the separate atoms. The balance of energy, released on combination, appears as the energy of motion of the molecule as a whole, that is, as heat. If the internal energy of the molecule happens to be greater

than that of the separate atoms, we get a cooling on combination. Further, if two molecules interact—that is, if they reshare the atoms of which they are formed—energy changes take place: the internal energy of the molecules which result from the resorting is not the same as that of the original molecules. In all combustions the internal energy of the molecules which are the products of combustion is less than that of the molecules existing before the combination takes place. To make the total energy before combination equal to the total energy after combination, the molecules formed must rush about more vigorously—that is, must have added energy of motion. This is only another way of saying that the products of combination are hot. We have transformed part of the energy which existed inside the molecules before they combined into external energy of the resulting molecules, which can be detected outside by the increased vigour with which they bang against other molecules. It is as if two heads of businesses went into partnership, cut down the internal running expenses, and put the money so saved into increased activity of their external operations.

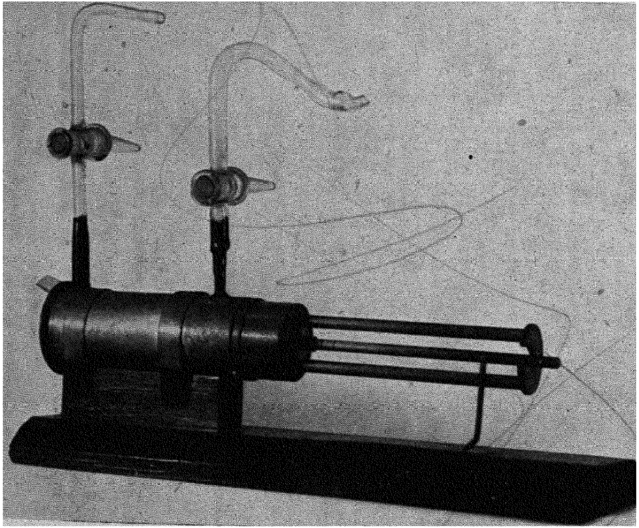
In every combination, then, we are, in a sense, using atomic energy, by modifying the energy of the uncombined atoms, and then turning the balance into heat, which is a form of energy easily converted into work. We are also, in most cases, at any rate, breaking atoms, the outside parts of atoms, in that in most combustions some of the atoms have to share or give up an electron. In any case it is quite easy to break an atom, in the sense of removing an electron, as we have seen in discussing the radiations from atoms: in

every tube containing glowing gas, millions and millions of atoms are having their outside electrons chipped from them, only to have them replaced a little later. In the ordinary way, however, when we speak of breaking atoms we are referring to the nucleus, as we shall discuss later.

In a sense, then, the utilization of atomic energy, and the breaking of atoms, is a very familiar process, which is going on all round us. The energy with which we are dealing, however, is comparatively small, and the electrons with which we tamper are outside electrons which are comparatively loosely attached. Also, we have done the atoms no permanent harm: if by chemical processes we separate them again from the molecule each will regain its old form, by taking up or giving up an electron, or electrons, and we shall have the original energy. To effect this separation, we should, of course, have to put energy into the system in some form or other, but the fact remains that atoms whose outsides are chipped are easily repaired. In a luminous gas they repair themselves.

We now turn to consider the nucleus, which is untouched by chemical action or by any physical effects, such as great pressure or high temperature, that we can produce in the laboratory. The nucleus itself is a very complicated structure: it is, in a manner of speaking, a minute molecule within the atom, for it is composed of protons and neutrons which are bound together in some sort of way. The binding forces are so great that any nuclear change involves relatively enormous energy changes. In a sense we may call the science of nuclear constitution, combination and disintegration, which has produced such devastating

PLATE V

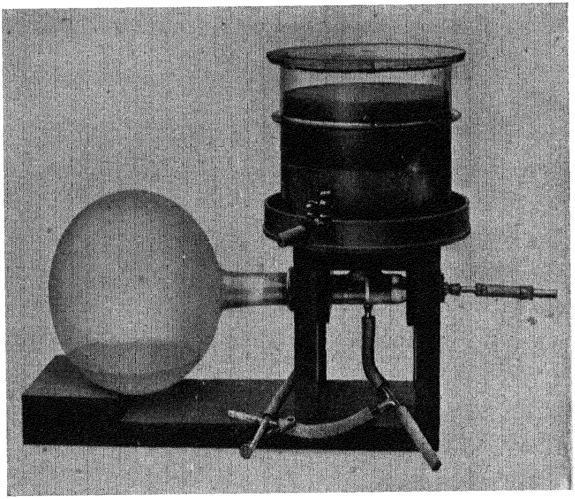


(*a*) Rutherford's original nuclear disruption apparatus.

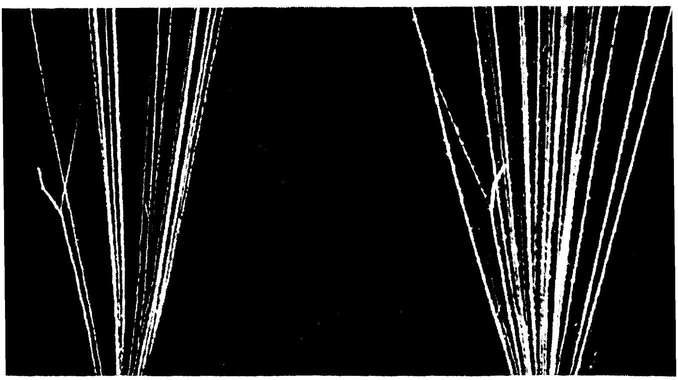
(*b*) Rutherford holding the apparatus with which he first obtained nuclear disruption.

From photographs lent by Sir Lawrence Bragg.

PLATE VI



(*a*) An early Wilson cloud chamber.



(*b*) Wilson cloud chamber record of disruption of nitrogen nucleus by an alpha particle. *Photograph by P. M. S. Blackett.*

results, nuclear chemistry or "the new chemistry," as I ventured to name it in a little book written some years ago.[1]

The first evidence that a change in the chemical nature of the atom was possible, and that very large energies were involved, was afforded by the study of radioactivity. Consider the case of radium. This element, which can be isolated from uranium, gives rise to three kinds of radiations. Firstly, alpha particles, which are nuclei of the element helium, having a mass approximately four times that of the proton and a positive charge of two units: they are shot off with a speed of some ten thousand miles a second and so have great energy. We have already mentioned that Rutherford took advantage of these natural atomic projectiles to determine the structure of the atom. A second kind of radiation consists of the so-called beta particles: they are electrons shot out with varying velocities, which in some cases approach that of light. The third kind of radiation is the gamma rays, which are not particles, but a kind of very penetrating X-rays.

Actually, the element radium does not itself give out all three kinds of radiations. What happens is that atoms of radium give out an alpha particle and in doing so become atoms of another element, the gas which used to be called radium emanation and is now known as radon. Radon is itself radioactive and gives out alpha particles, each radon nucleus that has lost a particle becoming a nucleus of a new element called radium A. This element in its turn emits an alpha particle and becomes radium B. Radium B emits not an alpha

[1] *The New Chemistry.* G. Bell & Sons Ltd. 1936.

particle, but a beta particle, and becomes radium C. Radium C is itself radioactive and is succeeded by other changes, some involving alpha particles and others involving beta particles; until finally an element is formed which is not radioactive, but stable—namely, lead. Some of the changes are accompanied by gamma rays, but they need not concern us at the moment. If the radium is shut up so that the radon cannot escape we have together all the elements involved in the series of changes and the specimen gives out alpha, beta and gamma rays.

The alpha and beta particles can be shown to proceed from the nucleus, and so naturally involve transmutations of the elements, for we know that what determines the chemical nature of an element is the charge on the nucleus. The alpha particle carries away two units of positive charge, and so leaves behind it the nucleus of an element two places lower down in the table of elements. The beta particle carries away one unit of negative charge, which is equivalent to adding one unit of positive charge, so that its loss corresponds to the formation of an element one place higher up in the table. It may be asked whence comes the beta particles, since the nucleus contains only protons and neutrons. The answer is that a neutron, with no charge, can turn into a proton, with one unit of positive charge, and an electron, with one unit of negative charge. This is what happens in a beta ray transmutation, the electron being emitted.

The facts of radioactivity, mainly disentangled by Rutherford, in conjunction with Soddy when the first great advances were made, showed, then, that a transmutation of the elements was possible. Uranium

itself is radioactive, and, through a series of changes, produces radium: radium is involved in a series of changes which ultimately produce lead. The atom, it then appeared, was not the essentially stable unit that the great scientists of the nineteenth century held it to be—at any rate some kinds of atom were not unchangeable.

The radioactivity of the elements of the uranium family and of the other two series of radioactive elements—the thorium family and the actinium family—is spontaneous: a certain fraction of the atoms present undergoes a change in unit time. It is usual to speak of radioactive decay, and just as some food substances decay, in the ordinary sense of the word, gradually and others rapidly, so do the radioactive substances. There is, however, an essential difference in the two kinds of decay. Ordinary decay, as of a piece of meat, is a chemical change, and we can hurry it or arrest it by ordinary laboratory processes. It is an affair of the outside atomic electrons, which we can easily control. The decay of any radioactive element, however, is not affected by any ordinary laboratory processes. However the particular elements are prepared, in whatever state of chemical combination they are, at whatever temperature or pressure they are, whether dry or in solution, they go through their changes in exactly the same way. This is what we should expect of a nuclear change, for we know how well the nucleus is protected by its bodyguard of electrons from most outside influences—though not, as we shall see, from certain particles. Some of the transmutations take place quickly, others slowly, but the rate of decay, the rate of each transmutation, is fixed.

Perhaps this expression, "rate of transmutation," requires a word of explanation. If we have a specimen of a radioactive element, radon say, we find that in a given time interval a certain fraction of the atoms in it are transformed. We call the time taken for half the specimen to transform itself, the half value period: for radon this period is about 3·85 days. This means that, starting with any given amount of radon, in 3·85 days half of it will have become radium A: in another 3·85 days, half of the remainder will have become radium A, so that 7·7 days from our start we shall only have a quarter left: in 11·55 days from the start we shall have an eighth left, and so on. This is a purely statistical or "on the average" law. We cannot say whether a particular atom will break down at any particular moment: all we can say is that, of a very large number of atoms, a certain fraction will have changed in a particular time.

The half value period varies enormously from element to element. For uranium it is very great, about five thousand million years: clearly, if it were not very great, all the uranium in the world would have changed into lead in the course of geological time. As it is, a certain proportion of lead is always found in conjunction with uranium, and, it being possible to show that this lead has come from the uranium, the proportion gives us one way of finding the age of the earth, namely, the time needed to grow this amount of lead. The half value period of radium itself is one thousand six hundred and ninety years. For some elements the half value period is measured in seconds, or fractions of seconds.

The radioactive elements are, then, unstable; some

very unstable, so that nearly the whole amount transforms in a very short time, others nearly stable, so that only a very small fraction transforms in a long time. It may be noted that all the natural radioactive elements have very heavy atoms. Uranium, thorium, actinium, radium and radon, for instance, have the highest atomic weights of all the elements. It looks as if nuclei could not be built up of more than a certain number of particles without becoming unstable.

If the possibility of atoms changing their nature is the first great lesson of radioactivity, the second is that very large energy changes are involved in those transmutations.

In the early days of radioactivity it was observed that a quantity of radium kept itself permanently at a higher temperature than the surroundings: it was self-heating. Subsequent measurements showed that one gram of radium gave out every hour about one hundred and forty calories, an amount of heat sufficient to boil nearly a quarter of a gram of water. This may not sound very much, but it must be remembered that it takes about one thousand six hundred years for half the radium to transform itself to lead, and that during all this time heat is being produced, although at a diminishing rate, owing to the fact that there is less radium left as time goes on. Calculation shows that the *total* heat which one gram of radium, with its products, gives out in its whole life is about the same as would be produced by the burning of three hundred and fifty thousand times its weight of coal, or the energy liberated in its whole life by about a tenth of an ounce of radium is equivalent to that of a ton of coal. In other words, the energy given out by one atom changing its nature is hundreds of thousands times

that which appears per atom in any chemical change, in which an atom simply combines with other atoms. Most of the energy appears as the energy of moving particles, such as, in particular, alpha rays, and this is converted into heat when the particle is reduced to comparative rest by collision with the atoms and molecules through which it passes. The very high energy of one particle moving in a particular direction is converted into the energy of irregular motion of a large number of molecules, which constitutes heat.

Radioactivity is a nuclear change in certain kinds of heavy atoms which nature has provided for us. The question arose in Rutherford's mind as to whether it might be possible to provoke a nuclear change in the laboratory, and thus artificially to transmute elements, to change one kind of atom into another, which was the old dream of the alchemists. It is clear that ordinary laboratory methods, high temperature and pressure, are powerless, but the alpha particles, which the natural radioactive substances themselves emit, furnish a very powerful weapon of attack. They are slower than the beta particles, but, on account of their much greater mass, have greater energy and can smash their way right up to the nucleus. Being positively charged they are, of course, repelled by the positively charged nucleus, and the greater the charge on the nucleus, the greater this repulsion. There is, therefore, the greater chance of a really close approach if the nucleus that is being attacked has a small atomic number, and the experiments which proved the possibility of artificial transmutation were carried out with light elements. They were performed in the Cavendish Laboratory at Cambridge by Rutherford.

In all but his first experiments he was aided by his collaborators, in particular, Chadwick.

The method used in the early experiments on artificial transmutation was to make use of the fact that a single swift particle can produce a minute momentary speck of light, called a scintillation, on a phosphorescent screen, which scintillation can be observed by a low-power microscope. This is the effect that Rutherford utilised in his experiments on the scattering of alpha particles that revealed the nuclear nature of the atom (see Chapter V). The distance which a swift proton thrown forward by the impact of an alpha particle can travel through a gas is much greater than that of the original alpha particle. Therefore, if by the phosphorescent screen we can detect particles far beyond the range of the incident particles, they must be protons knocked forward by the alpha particles, and, if no hydrogen is present, they can only come from the nuclei of the atoms in the gas which is being bombarded. It was on such simple reasoning that Rutherford based the experiments which showed that a proton could be knocked forward out of the nitrogen nucleus by the impact of an alpha particle. The simplicity of the means by which this fundamental fact was established is shown by the pictures in Plate V. At (*a*) is a photograph of the apparatus: at (*b*) is an old photograph of Rutherford himself holding the apparatus, which gives a key to its size. That the particles which produced the long range scintillations were really protons was proved by experiments on their deflection in a magnetic field.

When an alpha particle, then, strikes the nucleus of a nitrogen atom fair and square, so that it comes into

close contact with it, a proton is driven out from the nucleus, which itself takes up the alpha particle and becomes an isotope of oxygen. An oxygen atom can be artifically manufactured from a nitrogen atom. This does not mean that oxygen can be made by this method from nitrogen on a scale that could be detected by ordinary chemical methods. The number of alpha particles which issues per minute from even one gram of radium—a very large quantity for this rare element—though a very large figure, is very small compared to the number of atoms in a weighable quantity of gas, and of these alpha particles only a minute fraction make a favourable collision with a nucleus. It can be calculated, in fact, that if all the alpha particles from one gram of radium were allowed to fall on nitrogen for a year, the protons set free would amount to considerably less than a ten-thousand-millionth of a gram, which, even if it were multiplied by a thousand, would still be a quite unweighable quantity. Rutherford was only able to establish the fact of transmutation because his methods dealt with single atoms.

The further experiments of Rutherford and Chadwick on the action of swift alpha particles showed that protons could be driven out of many other light nuclei, with the result that the atoms were transmuted. In certain cases they were able to prove that the energy of the particle that came out was greater than that of the bombarding alpha particle, so that the result of the transmutation was a gain of energy, which could only have come from the energy of the transformed nucleus. We have not a case like that of a ball knocking a skittle out from the ring, when the energy with which the skittle travels must always be less than that which the

ball possessed before impact, but rather a case of some kind of trigger action, as if a ball were to push aside a catch which released the energy of a wound-up spring, which in its turn discharged the skittle with great energy. Once more, the effect, the release of energy, was proved for single atoms only, but the principle was established that nuclear energy could be artificially released.

A striking proof of the accuracy of Rutherford's deductions concerning the transmutation of the nitrogen nucleus was furnished by Blackett, who, as the result of a long series of trials, succeeded in securing a cloud chamber record of the track of a proton expelled from a nitrogen nucleus by an alpha particle (see Plate VI *b*). The two pictures show the same bundle of alpha particles, photographed from two different directions. At the extreme left of the left-hand picture can be seen a forked track, of which the thicker branch indicates the path of the struck and transformed nucleus, while the thinner, longer branch is the track of the expelled proton. The same forked track is next to the extreme left in the right-hand picture. These photographs, taken in 1925, can be said, then, to show the manufacture of a new atom from a nitrogen atom. Photographs taken with the Wilson cloud chamber have since then been one of the standard methods of investigating artificial atomic transmutations and have furnished very valuable results. Another method now widely used for detecting single swift particles is furnished by the Geiger-Müller counter, already described, and similar devices. The scintillation method, which is very trying on the observer, has been superseded by these automatic methods of recording.

The artificial transmutation of the elements, and with it the theoretical possibility of releasing nuclear energy, was thus established by the use of alpha particles. It would require a potential of 7·7 million volts to give to a singly charged particle an energy equal to that of an alpha particle, but the trouble about alpha particles is that, when we are talking in atomic figures,[1] there are so few of them, especially when we consider that only about one in a million produces a nuclear transmutation. One of the great needs for experiments on transmutation is, therefore, a copious laboratory source of particles possessing high energy.

One way to win such a source is to obtain, in some way or other, a very great difference of potential in an evacuated tube and to feed in charged particles, which will be accelerated by the electric field and acquire great energy. To produce in this way particles with energy equal to that of the alpha particles used by Rutherford would require, as we have said, over seven million volts, but it can be shown from theory that particles of less energy should suffice for transmutation, although they will be less effective; that is, it will require many more of them to disrupt a given number of atoms. Cockcroft and Walton, in Rutherford's laboratory, built up an installation producing a potential of some hundreds of thousands of volts, which, applied to a specially designed tube, produced beams of swift protons and deuterons, the deuteron being the nucleus of heavy hydrogen. With these particles atomic transmutations were effected which were most clearly

[1] It is true that a gram of radium gives out two million million particles per minute, but this number of hydrogen atoms, for instance, only weighs a few million-millionths of a gram.

revealed by Wilson cloud-chamber photographs. A particularly striking example of a transmutation produced with particles artificially speeded up in this way is that, when swift protons were directed on to lithium, a swarm of swift particles were produced which turned out to be helium nuclei; that is, artificial alpha particles. The mass of the isotope which is concerned in the transmutation[1] is 7 units and the nuclear charge is 3 units: the mass of the proton is 1 unit and its nuclear charge is 1 unit. The proton and the lithium atom together, therefore, have mass number 8 and charge 4, which suffices to make two helium nuclei, each of mass 4 and charge 2. Plate VII shows the transmutation of lithium into helium by proton bombardment, as revealed by a cloud-chamber photograph. Another striking transmutation produced by proton bombardment was, as shown by Dee and Gilbert, the change of a boron atom into three helium nuclei. These transmutations are examples of the new chemistry of the nucleus.

The outfit of Cockcroft and Walton was followed by many other devices of ingenious design for producing high voltage, some specializing in very high potentials, and other, such as one built by Oliphant and Harteck under Rutherford, giving very large quantities of particles at smaller, but still large, potentials. The number of transmutations produced depends upon both the energy of the individual particles and their number. As an example of the strange transmutations brought about with the last-named outfit, we may cite

[1] Lithium consists of two stable isotopes of which the commoner is of mass number 7. Mass number 6 constitutes about 8 per cent of the atoms.

that when heavy hydrogen—deuterium—is bombarded by swift deuterons (that is, when relatively motionless nuclei of heavy hydrogen are exposed to a hail of similar nuclei in rapid motion) helium nuclei of mass 3 and neutrons are produced. Of course, transmutations are relatively rare; about one for every hundred thousand swift deuterons in a typical case.

With the devices so far mentioned, if we want to give a charged particle the energy corresponding to, say, five hundred thousand volts, we have to produce five hundred thousand volts and let the particle acquire energy of motion in this field. It might seem that this is a truism, and that we would inevitably have to proceed in this way. This, however, is not the case. The ingenious and highly successful cyclotron, developed by E. O. Lawrence and his collaborators in California, produces particles with energies of millions of volts with potentials of only tens of thousands of volts. For his work on the cyclotron Lawrence was awarded the Nobel Prize in 1940.

The action of the cyclotron depends upon the fact that when a charged particle is moving with a certain speed in a magnetic field, directed at right angles to its path, it describes a circle—thus if the particle were moving in the plane of the paper of this page, as it lies on a table, and if the direction of the magnetic force were vertical, the particle would describe a circle in the plane of the paper. A further fact which is essential for the cyclotron is that, whatever the speed of the particle, it takes the same time to describe the circle, for the following reason—the swifter the particle the less its path is bent aside from its direction at any moment, and so the larger the circle: in fact, double the speed

means double the radius of circle, and so on. It follows that the time to go once round is fixed. We leave out of account certain complications produced at very high speed by relativity effects.

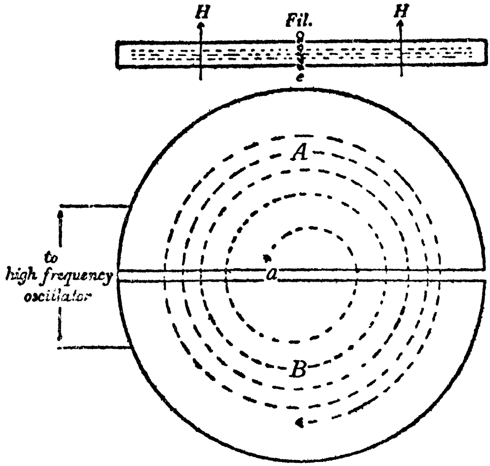


Fig. 12. The principle of the cyclotron.

In the cyclotron are two flat semicircular chambers called "dees," from their shape. In the diagram, Fig. 12, they are shown in section above, and in plan below. A very strong magnetic field acts at right angles to the flat faces; that is, perpendicular to the page if we are considering the lower diagram. Between the two dees is applied an alternating potential of, say, ten thousand volts; that is, the dees rapidly interchange the role of positive and negative. Near the centre, at *a*, is an arrangement for pushing positively charged light nuclei, say protons or deuterons, into the chamber. Owing to the magnetic field the protons describe part of a circle and, on coming to the gap between A and B,

are driven from positive A to negative B, acquiring an additional speed corresponding to ten thousand volts. Having acquired a greater speed, they now describe a larger semicircle. When they come to the gap between B and A they would be driven back if A remained positive, but things are so arranged that by this time A has changed to negative and B to positive, so that the particles are driven onward, and now, in addition to the speed with which they started, have that corresponding to twenty thousand volts. So the particles sweep on in ever widening circles: whenever they arrive at the gap they find the direction of the electric force such that it urges them on, which is possible, because of the equal times required to describe each semicircle, great or small. Every complete revolution is equivalent to an energy gain of twenty thousand volts, so that a hundred revolutions is equivalent to a potential of two million volts, although the voltage applied is only ten thousand volts. Finally, the particles are pulled aside by a charged deflecting plate and pass out through a thin window into the outside air or on to any target that may be provided. Plate VIII shows a beam of swift particles issuing from a cyclotron and rendering the air in their path luminous.

To-day, even leaving the latest instrument out of account, particles with energies corresponding to sixteen million volts have been produced in such numbers that their total energy equals that of the particles from thirty tons of pure radium. The particles usually accelerated by the cyclotron are protons, deuterons and helium ions—artificial alpha particles. Cyclotrons can also act as powerful sources of neutrons,

since these are produced by the impact of swift protons or deuterons on beryllium.

Plate IX shows the Berkeley cyclotron which as early as 1935 established the great possibilities of the instrument. In the centre of the picture are the pole pieces, with the dees, attached to which are the various connections, between them. The great cylindrical boxes contain the windings, cooled by oil circulation, which carry the current to energise the electro-magnet. Round them, above and below, extends the yoke which connects the pole pieces. On the left is Dr. R. L. Thornton, and on the right Dr. Edwin Macmillan, two of the Berkeley team. The magnet weighs about 85 tons, which is the weight of a fair sized locomotive, and the energy of the particles produced is about 5 million electron volts. Since this was constructed a cyclotron has been built, also in California, with a magnet weighing two hundred and twenty tons, which gives particles of an energy of sixteen million electron volts and more.

Still more recently an even much larger cyclotron, which is shown in Plate X, has been put into operation at the Radiation Laboratory at Berkeley. The magnet yoke is constructed in the form of a closed oblong frame, about 56 feet long and 30 feet high, with the poles, 184 inches in diameter, in the middle, as usual. The magnet is largely made of two-inch steel plate, and weighs 3,700 tons, with 300 tons of copper in the windings. The poles are made of thicker plates. The apparatus for the radio frequency supply is seen on the left and the scale may be judged by the man beneath it. The principle of this newest cyclotron, which is called a synchro-cyclotron, is somewhat different from that

of older installations, but would require rather more elaborate explanation than is here possible. This instrument has produced deuterons and alpha particles of energy equivalent to that acquired by an electron in a potential fall of 200 and 400 million volts respectively, the energy of the alpha particle being double that of the deuteron because it has a double charge.[1]

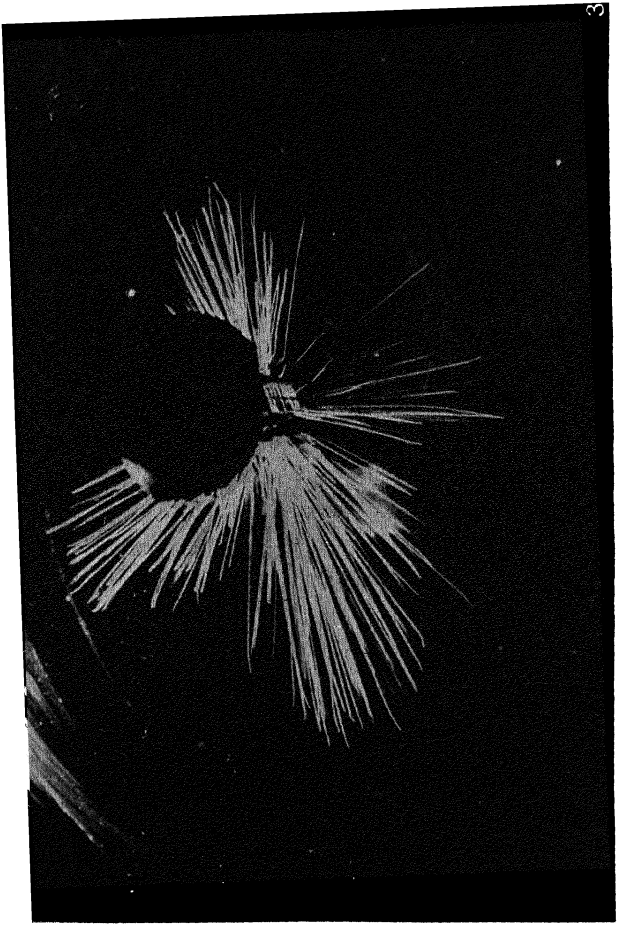
An instrument has also been made in which electrons are speeded up by being made to go round and round in a magnetic field, although the principle used is different from that of the cyclotron. This electron accelerator is called a betatron, since the swift electrons from radium are called beta particles. Energies of a hundred million and more electron volts have been produced.

It is thus now possible to dispense with radium as a source of swift particles, since swift protons, deuterons, helium nuclei, and electrons can be produced, by the machines which have been briefly described, in immensely greater quantities, and of greater energies, than is possible with radium. With these particles a great variety of nuclei have been transformed. In these reactions not only are atoms transmuted into new atoms, but radiations are in general produced which may be swift protons, or positive or negative electrons, or neutrons, that is, nuclear fragments of one kind or another, or their results.

Another very powerful agent for transmuting atoms is the neutron, as first extensively used by Fermi, who for this work received the Nobel Prize in 1938. The general reason that neutrons are so effective is easy to

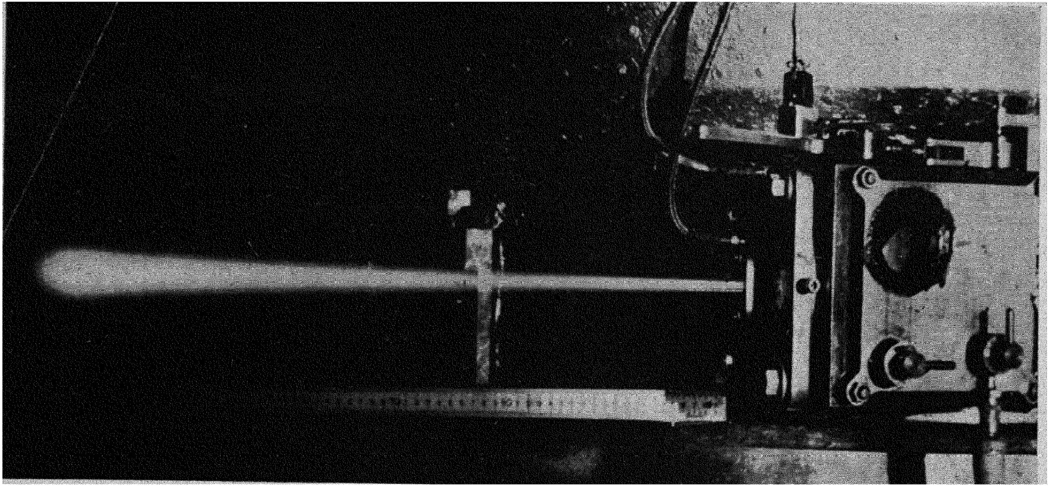
[1] I am indebted to Professor Donald Cooksey, Associate Director of the Radiation Laboratory, for the picture and information.

PLATE VII



The transmutation of lithium into helium by proton bombardment, photographed in the cloud chamber by Drs. Dee and Walton. *Reproduced by courtesy of the Royal Society.*

PLATE VIII



A beam of deuteron about two feet in length issuing into the air from the Berkeley cyclotron. Being composed of swift atoms the beam has a definite range, which in this case corresponds to about ten million volts.

see. Having no charge they are not affected either by the electron cloud or by the charged nucleus of the atom: in particular they can approach the nucleus without suffering the repulsion that acts on alpha particles and on swift protons and deuterons used in nuclear chemistry. Neutrons, as liberated in the nuclear reactions by which they are produced, have very high energies, corresponding to that of charged particles exposed to potential differences of millions of volts, but if they collide with hydrogen atoms, which have about the same mass, they give, on an average, about 60 per cent. of their energy to the atoms that they strike.[1] After a number of collisions all the energy that they have left is just that which the hydrogen atoms have, owing to their ordinary heat motion, or thermal agitation, to use the usual longer words. The neutrons have shared out until they are down to general energy level, when they are called "thermal neutrons." Since the forces of chemical binding do not affect nuclear impacts, it makes no difference if the hydrogen atoms are in combination instead of free, and, as the hydrogen atoms are thickly packed in solids, a hydrogen compound, such as paraffin wax or water, is frequently used for slowing down neutrons.

Swift neutrons and thermal neutrons can both produce atomic transmutations, but generally speaking, the behaviour of the reacting nucleus is different in the two cases. The slow thermal neutrons, which spend

[1] If a resilient ball strikes a much heavier resilient ball, it bounces back with nearly its full speed, and gives up little energy to the heavy ball. If the ball strikes one of its own mass fair and square, it stops and gives up all its energy to the other ball. If it strikes off centre, it retains some of its energy of motion, the 60 per cent. quoted being the average for all kinds of impacts. It is the fact that the hydrogen nucleus is no heavier than the neutron that makes it such an effective slower-down.

a comparatively long time loitering in the neighbourhood of the nuclei of the atoms through which they are passing, have a particularly good chance of being picked up, captured, by these nuclei, with the consequent formation of new nuclei. Swift neutrons can also be captured in particular circumstances, depending upon the energy levels in the nucleus. They are also particularly effective in producing transmutations in which a charged particle is at once emitted. The detailed consideration of the reaction of nuclei with neutrons is a difficult subject which involves so-called resonances, conditioned by the different states in which nuclei can exist, and consideration of the potential field round the nucleus.

We have already said that the radioactivity of elements such as radium and uranium can be neither hurried nor stopped. The natural radioactive elements are contained in certain ores and are separated out by chemical means. That radioactive elements could be manufactured was long held impossible. However, in 1934, F. Joliot and his wife, Irène Joliot-Curie, daughter of Madame Curie, found that when aluminium was bombarded by alpha particles it gave out positrons, indicating a nuclear change, and not only this, the emission of positrons continued after the bombardment by alpha rays had stopped. Further, after the bombardment had ceased, the activity of the aluminium diminished as time went on. In other words, the metal was behaving just as does a natural radioactive element, except that the radiation consisted of positive electrons instead of alpha, beta or gamma rays. Incidentally, the positrons were identified by cloud-chamber photographs taken

in a magnetic field. The activity of the artificially radioactive element formed from aluminium dies off pretty quickly, diminishing to half in a little over three minutes. The element actually formed is an isotope of phosphorus, an isotope which is unstable because it contains too much charge for its mass. The nucleus, therefore, after a short time, gives off one unit of positive charge and becomes a silicon isotope, which is stable.

Such artificially radioactive isotopes are indicated by putting the word *radio*—before the name of the element. Thus we say that radiophosphorus is formed from aluminium by alpha ray bombardment. Of course these isotopes are ones never found in the natural element, because if they had been formed at any stage they would quickly have changed to some stable isotope, like the silicon isotope just quoted, which is found in ordinary silicon. A general rule is that no nucleus is stable which contains more protons than neutrons—in other words, whose atomic number is greater than half its atomic weight.[1]

The Curie-Joliots soon formed several other artificially radioactive isotopes, some of which emitted a positive electron in the course of their decay, while others emitted an ordinary negative electron, the latter form of transmutation showing that cases can occur where the nucleus has too few protons for its neutrons. For instance, bombarding magnesium with alpha particles leads to the formation of an unstable isotope of aluminium—radioaluminium—which gives out in the course of its life ordinary electrons and becomes

[1] There is one exception, the helium isotope of mass 3, which is stable.

silicon. It can readily be realized that the possibility of artificially making unstable nuclei and studying their breakdown is of the greatest importance, and the Curie-Joliots were jointly awarded the Nobel Prize for Chemistry in 1935.

Since the time of the original discovery many other ways have been found for making artificially radioactive elements, but it is well to remember that it was the application of Rutherford's old trusty, the alpha particle, that originally led to the discovery. In particular, bombardment by neutrons has proved very effective; however, in laboratories that do not possess a cyclotron or other accelerating device alpha particles have still to be used for producing the neutrons. Artificially accelerated protons and deuterons have also been extensively used for manufacturing active isotopes. As examples of what has been done, the addition of a neutron to sodium produces an unstable isotope of the same element, radiosodium, which subsequently gives out an electron and becomes magnesium. From proton bombardment of carbon there results radionitrogen, which breaks down with emission of a positron. Deuteron bombardment of phosphorus gives radiophosphorus, which emits an electron when it decays. To-day several hundred artificial radioactive elements have been formed and for practically every element radioactive isotopes have been prepared. The half life of many of them is short, being measured in minutes or hours, but half lives of some or many days also occur commonly, and in one case at least the half life extends to years.

Radioactive isotopes are not only extremely important for the light they throw on nuclear structure: they

also have very valuable applications in biology. In problems of nutrition, of the general chemical machinery of the body, of plant growth and so on, it is of fundamental interest to know how the materials supplied at one place, or in one way, to the living organism are handed on through various processes of chemical combination and chemical breakdown, and to learn not only where they end up, but how long they take to get there. For instance, the proteins which are a constituent of certain classes of food, such as meat and cheese, contain the so-called amino acids, which in their turn contain nitrogen. It is important to know the vicissitudes of the nitrogen groups as they go through the body, until they are finally excreted. Or take phosphorus, which is a constituent of the bones: how long does it take phosphorus given in food—not as the element which readily catches fire, of course, but in combination, as, say, sodium phosphate—to be taken into the bone structure? These kind of problems have been solved by the use of isotopes.

If we introduce in place of an ordinary compound containing phosphorus, say, one in which the common isotope of phosphorus is replaced by a rare isotope, the substitute will be treated in exactly the same way by all the processes that take place in the body, because as far as chemical action is concerned all isotopes are undistinguishable. Physical methods, however, can distinguish between different isotopes, and we thus have a method of labelling the atoms so that we can trace them in their journeys. In particular, the radioactivity of artificially manufactured isotopes is easy to detect. Isotopes which are used to provide, as it

were, tagged or identifiable atoms are called "tracer elements."[1]

As an example of a tracer element we may take radiophosphorus, which is the 32 isotope of phosphorus produced, as already mentioned, by bombarding ordinary phosphorus, of mass 31, with swift deuterons from a cyclotron. An element of mass 33 and nuclear charge 1 greater than phosphorus (namely, sulphur) is formed, which instantaneously gives out a proton and thus becomes phosphorus 32. Phosphorus 32 gives out electrons, one for each atom, in the course of its radioactive decay, which is fairly slow: half the substance is transformed in about fourteen days. Radiophosphorus has been fed to animals in the form of sodium phosphate, and by its radioactivity it has been shown that in a matter of hours from the intake the phosphorus has become embodied in the bone. Radiophosphorus has also been used to follow the intake of phosphorus in plants. The radioactive isotope is introduced into phosphates placed in the soil in the pot and the radioactivity of the leaves, for instance, observed later.

Stable isotopes can also be used as tracers, but they are more troublesome to detect. The mass spectrograph, the instrument originally devised and used by Aston to separate and measure the isotopes in ordinary elements, is the device that discloses their presence. Stable isotopes, of course, exist already in the ordinary elements, but the method is to introduce abnormally

[1] Not to be confused with "trace elements," the name given to elements which, although present only in traces in certain living bodies, have very important effects. It has been shown, for instance, largely due to the efforts of Dr. H. B. Marston, that traces of copper and cobalt in pastures are essential to the well-being of sheep.

large quantities of an artificially prepared rare isotope as the tracer. Thus, it has recently been found possible to prepare relatively large quantities—of the order of a pound a week—of the 13 isotope of carbon, $C13$; this exists as about 1 per cent. in ordinary carbon, which is nearly all $C12$. If then, sugar, say, in which all, or nearly all, the carbon is $C13$ is eaten, and samples of body fluids are subsequently taken, the abnormal proportion of $C13$ found in them will tell us how much of the carbon from this particular delivery of sugar had arrived at the time the samples were taken. Heavy water, in which practically all the hydrogen is $H2$ instead of $H1$, can also be used as a tracer. Heavy water can be particularly easily identified by its density, which is some 10 per cent. greater than that of ordinary water. Even very small drops can be detected by the fact that they will fall through a liquid of the density of ordinary water: a liquid with which they do not mix must, of course, be chosen.

Although stable isotopes are not so easily followed in small quantities as radioactive isotopes, they have the merit that they cannot cause changes in the tissues of the body, as radioactive ones may do, especially if left there long. Both kinds of tracers, then, have their own advantages.

In recent years a new science has rapidly developed, in which one kind of atom is freely made into another kind of atom, which may either be stable and permanent, or may be radioactive, changing, sooner or later, with emission of a particle, into some other atom. The number of possible reactions is very great, and a whole new chemistry has developed in which the formulæ of the old chemistry, representing the combination and

breakdown of molecules by the interchange of atoms, are replaced by formulæ representing the combination and breakdown of nuclei, with the interchange of particles. One of the combining nuclei is always one of the light particles, it is true: so far no case has been discovered where two heavy nuclei combine, although, as we shall see later, cases are now known where heavy nuclei break up into two more or less equal parts.

Chemical formulæ, however, do not represent all the facts about a chemical reaction. The energy absorbed or liberated as heat is another important aspect, and in order to know if the reaction will go in one direction or another there are certain thermal, or energy, properties of the different substances taking part in the reaction which we require to know. The properties of the nucleus that fix how nuclear reactions take place—what new nuclei will be formed, whether they will be stable or unstable, what particles will be released and so on—are very complicated and are not yet fully understood, but there is one simple law of prime importance that we will now consider.

Although a nucleus is made up of protons and neutrons, its mass is not precisely that of the protons and neutrons that compose it. Let us take an example. For purposes of exact measurement the mass of the 16 isotope of oxygen is taken as exactly 16 units, or the unit of mass for atomic purposes is taken as one sixteenth of that of this isotope of oxygen.[1] On this scale the mass of the proton is not 1, but 1·00758: the mass of the neutron is 1·00893. Now the mass of the ordinary helium atom is 4·00388 or, allowing for the

[1] This was adopted from the chemical practice, for which there are good reasons, of taking the mass of the oxygen atom to fix the standard of atomic weight.

mass of the two electrons, the mass of the helium nucleus is 4·00280. But the mass of two separate protons plus two separate neutrons is 4·03302, so that packing them together to make up a nucleus leads to a loss of mass of 0·03022 units or nearly 0·8 per cent.

Einstein's work on the theory of relativity had led him to the necessary conclusion that mass and energy were equivalent, in the sense that heat and work are equivalent; that is, supposing that the one can be converted into the other, there is an exact conversion figure, or rate of exchange, which fixes the quantity of the one that appears when a given amount of the other disappears. The simple formula, which gives the energy value E of a mass m, is

$$\mathrm{E}=mc^2,$$

where c is the velocity of light. If m is measured in grams, c in centimetres per second, then E comes out in the units of energy called ergs.[1] This means, for instance, that if for any reason, and in any way, 1 gram of matter could be made to disappear completely as mass, it would be replaced by sufficient energy to give a million horse-power for thirty-three hours. A million horsepower is about the delivery of the power stations worked by Niagara, so that the performance of the famous falls is equivalent to the conversion of 1 gram of matter into energy every thirty-three hours.

Einstein's relation, then, shows us that if we could build up 4 grams of helium from protons—that is, from hydrogen—and neutrons, the loss of mass of 0·03022 grams would represent about a million horsepower for an hour. There is no suggestion so far that this particular bit of nuclear chemistry, the production of helium

[1] The foot pound is about thirteen million ergs. Thus the erg is a very small unit.

from hydrogen, is likely to be performed on earth, at any rate yet awhile. There are, however, good theoretical reasons for supposing that the heat of the sun is due to the energy set free when hydrogen is converted into helium and positrons, four hydrogen atoms going to each helium atom, and two positrons being set free. The reaction, suggested by Bethe, is a fairly complicated one, taking place in six stages and involving carbon, nitrogen and oxygen nuclei in its course. The heat of the sun being due, then, to nuclear changes, or "building the atom," as our friends who speak of "splitting the atom" might put it, and all our wind power, water power, coal and other fuels and so on being ultimately derived from solar energy, we can say, with some degree of justice, that all our present sources of energy are, in the end, atomic. To keep up the sun's present temperature—that is, to supply the energy lost by radiation—requires the formation of, roughly, four million tons of helium per second, which sounds a great deal until we remember that the mass of the sun is about five hundred million million million times as great as this. It will be a long time before all the hydrogen in the sun is used up.

The Einstein energy relation has been verified in the laboratory in the transformation of single atoms. A particular case is that of the impact of a proton on the 7 isotope of lithium (lithium seven, as it is spoken; Li7, as it is often written); a nucleus mass 8 is formed, which immediately breaks into two helium nuclei, shot off at high speed. The transformation can be photographed in the cloud chamber, and from the length of the tracks of the swift helium nuclei their initial velocity can be calculated, which gives us their energy of motion.

Once more the cloud chamber gives us details of reactions in which single atoms are involved.

Now the mass of the lithium nucleus is 7·01640, which, with the mass of the proton added, gives 8·02398 as the mass of the two parts before the reaction: the mass of two helium nuclei is 8·00560, which is less than that of the particles from which they are formed by 0·01838 units. This figure, then, represents mass which disappears in the nuclear reaction. Now the energy of motion with which the two helium nuclei leave comes out at a figure which, when changed into mass by Einstein's relation, is 0·0182 mass units, which agrees with the mass loss within experimental error. Similar measurements have been made in other nuclear reactions and it has been found that the energy given to the particles as motion always equals the loss of mass, if Einstein's conversion figure is used.

Of course, even in ordinary chemical combination, as in, say, the action of sulphuric acid on copper to form copper sulphate, energy may be produced in the form of heat, and there will be a corresponding change of total mass in the course of the reaction. The disappearance of mass equivalent to the energy set free is, however, minute. Let us consider the case of carbon —coke, if you will—burning in air to form the gas carbon dioxide. For every gram which is consumed about eight thousand calories appear, which is an energy equivalent to a mass of about 3·7 ten-thousand-millionths ($3{\cdot}7 \times 10^{-10}$) of a gram. No wonder that the elaborate attempts made at different times to detect a change in mass due to chemical action all failed to give a positive result. If the effect had been a thousand times bigger it would still have escaped detection.

VIII

THE RELEASE OF ATOMIC ENERGY

"And tho', I own, if I was a Prince, I would generously recompense the scientifick head which brought forth such contrivances;—yet I would as peremptorily suppress the use of them."

LAURENCE STERNE. *Tristram Shandy*. Volume II. Chapter 14. 1759

Faust. Da muss sich manches Rätsel lösen.
Mephistopheles. Doch manches Rätsel knüpft sich auch.[1]

GOETHE. *Faust*. Walpurgisnacht.

THE experiments of Rutherford and his school, of Fermi, of the Curie-Joliots and many others had clearly shown that a very great variety of nuclear change could be produced at will, and further that in certain atomic transmutations nuclear energy could be released, the energy appearing as energy of motion of swift particles. In principle, then, the possibility of deriving energy by tampering with the atomic nucleus had been abundantly demonstrated by 1938. From the practical point of view, however, the situation was that even by the application of thousands of pounds worth of apparatus the effect could be obtained with a comparatively few atoms at a time, so that the total energy freed in months would be very much less than that given by the burning of a single drop of petrol.

[1] *Faust*. There many a riddle must unravel.
Mephistopheles. Yet many a riddle there is set.

Walpurgis Night, the eve of May Day, was the occasion of the great witches' Sabbath on the Brocken, which gives the quotation a certain appropriateness.

It was as if, in the far beginnings of mankind, some experimenter had found it possible, by very great effort, to strike sparks from flint and so to set fire to odd single blades of dry grass, a fresh effort being necessary for each burning blade.[1] The possibility of fire would have been demonstrated, but there would be no question of cooking or other service until man had found out how to build a fire, how to make the heat of one burning blade of hay set fire to other bits of fuel, which in turn would each set fire to other bits, until in the end the source of heat would maintain itself as long as fuel was provided, without any fresh effort in the way of striking sparks. This suggests that, to obtain any appreciable amount of atomic, i.e. nuclear, energy, we require a method by which one atom, transforming with release of energy, shall cause other atoms to transform, which in their turn shall provoke transmutation in other atoms, until large quantities of matter are involved, with wholesale release of energy. The process should maintain itself, once it has been started, as long as new material, to be transformed, is supplied. Such a reaction, in which change in one small part, an atom or molecule, provokes similar changes in other parts, which in their turn spread the process of change, is called a chain reaction.

In 1934 certain puzzling results were found to be produced by the bombardment of uranium with neutrons. It appeared that, as was to be expected, a heavier isotope of uranium had been produced, and also that a new element, of greater nuclear charge than

[1] It was a legend of ancient Greece that Prometheus stole fire from heaven for man, and brought it down concealed in a hollow nut. "Nucleus," in Latin, means a nut, so that Rutherford may be justly called our modern Prometheus.

uranium, had resulted, but there were complications that were not solved until 1938, when Hahn and Strassman made the astonishing discovery, announced in January 1939, that one of the products of the bombardment of uranium with neutrons was an isotope of the element barium, the weight of which atom is not much more than half that of the uranium atom. This implied, as was soon realized, that the uranium atom had not, as in the nuclear changes previously studied, been deprived of, or enriched by, an odd particle—a proton, an alpha particle, or an electron—but had been broken into two more or less equal parts. The atomic nucleus had not been chipped, but had been split into two.

One of the first to realize the fundamental significance of the discovery of Hahn and Strassman, and its implications, was Niels Bohr, who was at the time, early in 1939, in America. He had recently arrived from Copenhagen, where Frisch and Meitner had just come to the conclusion that the absorption of a neutron by a uranium nucleus could lead to its division into two roughly equal fragments. As a result of an address which he gave on the subject at a conference of physicists in Washington, intensive research on the subject began in laboratories all over the world. In a general account of this kind it is not necessary to try to apportion credit to the various workers who made advances. Rutherford had died in 1937, in full vigour at the age of sixty-six, or we might have known the truth sooner. Joliot, Fermi, J. A. Wheeler, L. A. Turner, J. R. Dunning and many other names occur in the early history of the research on nuclear fission, as the splitting of the nucleus is

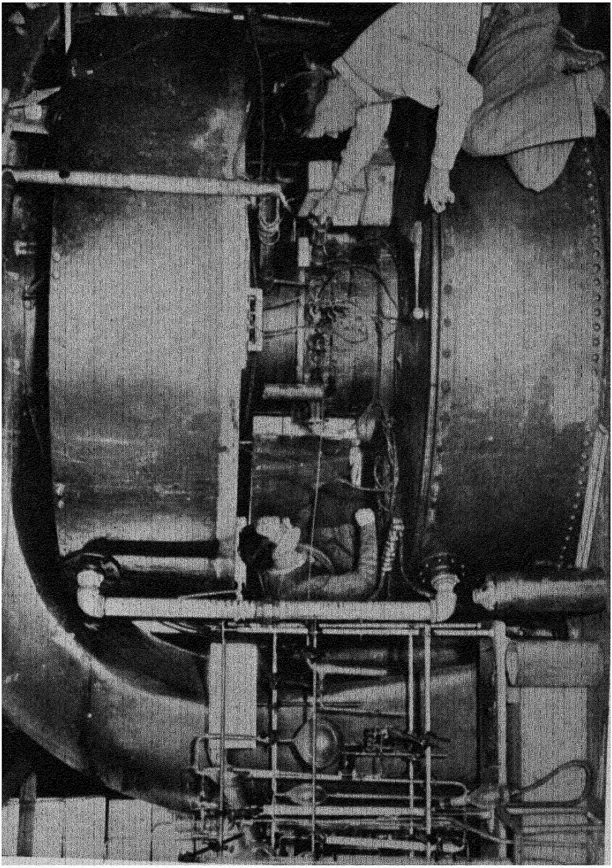
generally called. The outbreak of war in Europe had the effect that much of the work was done in America, where the great native genius had been reinforced by many of Europe's best scientists, driven from their homes by Nazi and Fascist rule.

There are three fairly straightforward ways in which nuclear fission of single atoms, with large release of energy, was demonstrated. It must be remembered that the energy appears as the very high velocity of the two fragments, just as the energy of the explosion in a revolver cartridge appears as energy of motion of the bullet and energy of motion of the recoiling pistol when the shot is fired. This picture, however, corresponds most closely to the discharge of an alpha particle by a radioactive atom: to make it valid for our present case the pistol should weigh about the same as the bullet, so that the energy of recoil and the energy of the bullet are about equal. One way in which the flying fragments make themselves evident is by producing positively and negatively charged atoms, the so-called ions, in the air, or other gas, through which they move. We learnt in Chapter V that there were two ways in which these could be detected, either by amplifying the electrical effect produced and making it register itself on an instrument, as is done with the Geiger counter, or by taking pictures with the help of the Wilson cloud chamber. When uranium in an ionisation chamber was bombarded with neutrons ionisation effects, which were amplified and registered by kicks of the oscilloscope, were observed: they corresponded to particles of enormous energy, such as it would require a hundred million volts or so to produce. The Wilson cloud chamber gave evidence of

tracks, associated with very heavy ionisation, resulting from the bombardment of uranium by neutrons. That the actual particles producing the tracks were very massive compared to, say, alpha particles, was also indicated by the way in which they brushed oxygen nuclei violently aside, to form short tracks, without being themselves deflected appreciably. A third method by which the heavy fragments were detected was by their recoil: a collecting plate placed in the neighbourhood of bombarded uranium became radioactive in circumstances that meant that the radioactive atoms must have been flung to the collector with energies that they could never have acquired by, for instance, the recoil from alpha or beta particle discharge. These are just indications of the method which convinced the world of science that the uranium nuclei had really been split.

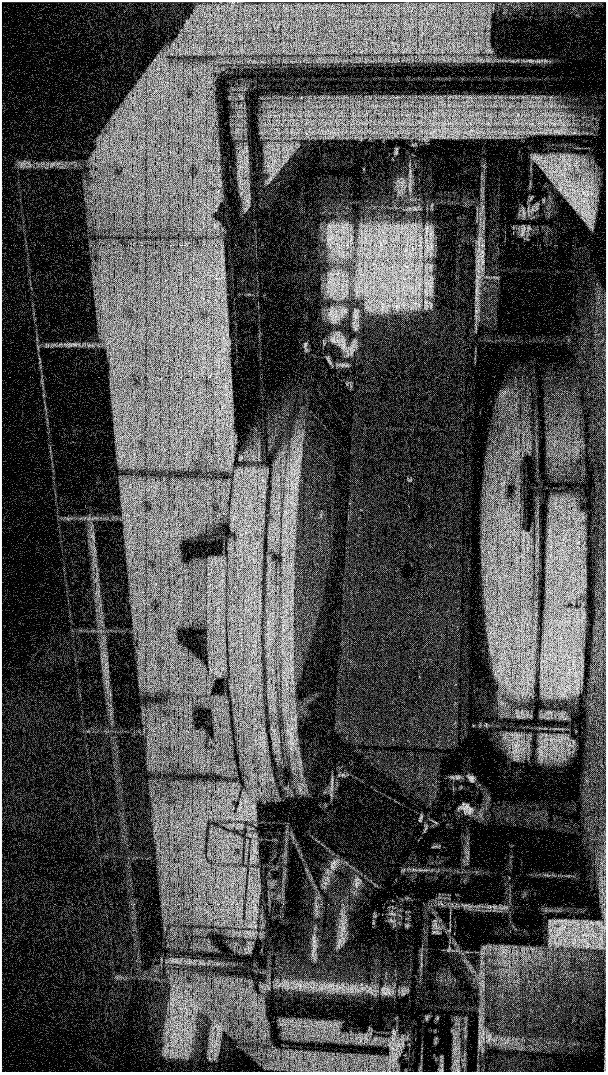
The next essential thing to be established was that the fission was accompanied by the emission of neutrons. This was to be expected, because it was known that the heavier the atom, the bigger the proportion of neutrons in the nucleus. Thus, uranium has an atomic number 92, which means 92 protons, and the lightest uranium isotope is of mass 234, so that there must be in it 142 neutrons, or the proportions are about 1·54 neutrons to each proton in the lightest isotope, and more in the heavier ones. As an example of an atom of medium mass, take barium: here the atomic number is 56 and the mass number of the heaviest isotope is 138, which means 82 protons, so that the proportions are about 1·46 neutrons to each proton. As this is typical, it means that if two atoms of medium mass are made out of a uranium atom, there should be neutrons

PLATE IX



One of the Berkeley cyclotrons.

PLATE X



The new synchro-cyclotron at Berkeley.

over. This was soon verified and it was then evident that the possibility of a chain reaction was at hand. It was not certain that such a reaction would take place, because the number of neutrons might not be sufficient. In fact, it was clear that in some circumstances it would not be sufficient, since plenty of uranium had been lying about in the ore as fairly concentrated uranium oxide for hundreds of millions of years, during which time it must have been frequently hit by neutrons released by cosmic ray processes, and it has not produced any explosive reaction. Clearly, in these conditions too many neutrons escape, or are captured in some non-destructive way, for the action to be cumulative. Let us now examine the situation briefly in the light of our present day knowledge, without attempting to trace the steps by which the advances were made.

The general scheme of a chain reaction is shown, purely diagrammatically of course, in Fig. 13. The black spots represent neutrons and the white protons, but it must not be imagined that the particular arrangement of these spots shown in the pictured nucleus has any significance. Further, the effect of neutron speed, shortly to be discussed, is neglected. In I a neutron is shown about to strike the nucleus. In II the result is shown: the nucleus splits into two parts and a few neutrons, here shown as three, issue. In III one neutron is represented as lost, owing to one of the causes soon to be mentioned: the other two are each about to strike a nucleus and produce fission. In IV the fission is shown taking place, each nucleus producing three more surplus electrons, of which one is supposed to be lost as shown in V, where five nuclei are about to be struck. In VI the fission of these further nuclei

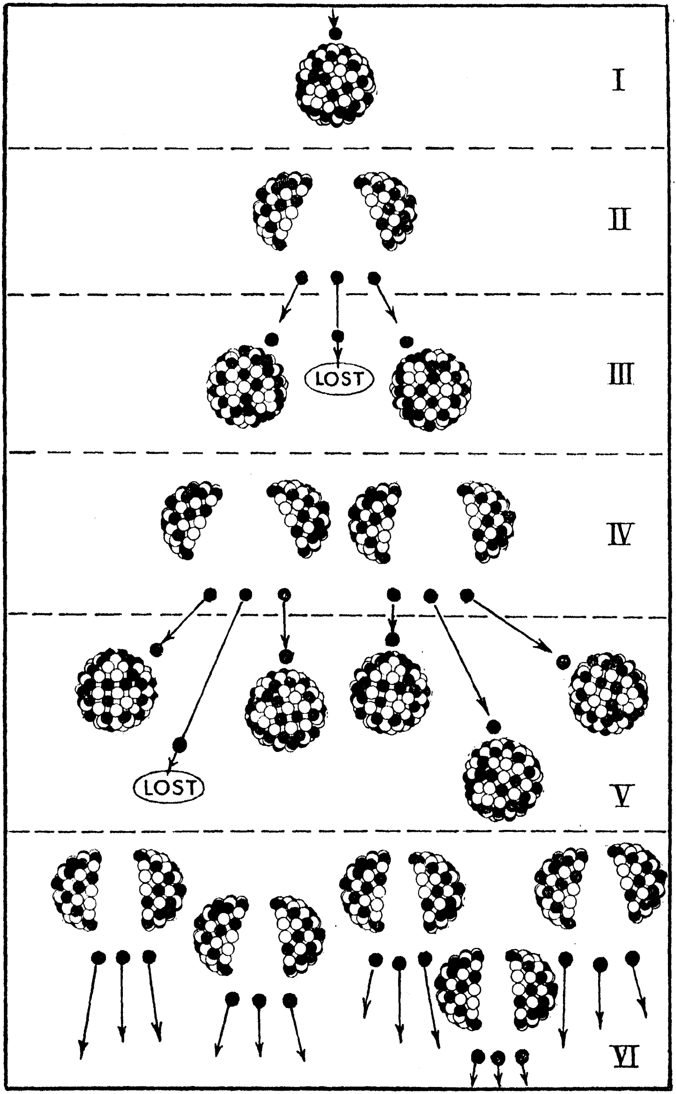


Fig. 13. Pictorial scheme of a chain reaction.

is shown. This is a chain reaction. If, owing to circumstances, two of the three neutrons were lost at each stage, the process would just be maintained, and if a larger proportion was lost the process would not spread at all.

The effect of neutron bombardment on uranium depends both on the energy of the neutrons (for slow neutrons and fast neutrons have different actions on different nuclei) and on the particular isotope in question. If we are trying to promote a chain reaction we want as many of the released neutrons as possible to cause nuclear fission, and as few as possible to be captured without fission or to escape altogether out of the lump of uranium. We can see at once a point that is of fundamental importance: the bigger the lump the bigger the chance of a chain reaction. Consider a sphere, for instance: if we double its diameter, its mass goes up eight times, but its surface increases only by four times. In general, the bigger it is, the less surface there is for, let us say, every million atoms present. Now with neutrons being liberated and going in all directions this means that the chance of a fission-producing hit rather than escape is increased by increasing the size of the lump, and, in particular, that if the lump is quite small the chance that a neutron will escape before it produces fission is quite large and there will probably be no chain reaction.

Escape, or a hit that produces fission, are, however, not the only two possibilities that confront the neutron released in uranium. There is also the chance that it may be captured by a uranium atom without producing fission and the chance that it may be captured by an atom of some other element present as an impurity.

The effect of impurities is more serious than it might at first appear, because quite a small proportion of atoms offer quite a big target. Imagine, for example, a million peas arranged in a cubical box. If one in a thousand is a black pea the chance that a skewer stuck down right through the box will hit a black pea is not one in a thousand, but something like one in twelve. This is, of course, only a rough illustration, but may help to an understanding of why, in nuclear reactions, the question of purity so often arises.

Supposing, however, that we have a lump of pure uranium, the chance that a neutron, in running a given distance through it, will produce a fission—and hence the chance of a chain reaction being set up—will depend upon both the speed of the neutron and upon the particular isotope of uranium that is in question. The fundamental theoretical problem, then, is to estimate this chance, and to do this demands some knowledge of nuclear structure and of the forces that hold nuclei together.

This is one of the most difficult questions of physics. Ordinary positively charged particles repel one another, so that it is clear that within the nucleus there must be other forces besides the ordinary electrostatic ones, or a structure of positive and neutral particles—protons and neutrons, that is—would blow itself to pieces. It is assumed in modern theory that when the particles are very close together there exist special forces, the so-called short range forces, which are attractive, and hold the assembly together. They act between neighbouring particles and are of a particular type, discussed in the new quantum theory, called "exchange forces."

The consequence is that it is possible for the nucleus to be an assembly of particles close to one another, unlike the electrons in the outer part of the atom, which can be considered as a sparse system. Bohr it was who first compared the nucleus to a liquid drop, and many of the properties of large nuclei have been discussed in terms of this "drop" theory. The passage of a neutron into the nucleus gives energy to it, which is rapidly shared between the particles: this corresponds to warming a drop. Ultimately a particle may be emitted by the nucleus, which corresponds to evaporation. Or the nucleus can be set into vibration, just as a drop may be, with the result that it splits into two, the repulsive forces, when the nucleus takes an elongated shape, overcoming the short range forces, which are most effective when the nucleus is spherical. When the nucleus is large it is more likely to break up than when it is small, because the attractive forces have a very short range compared to the repulsive forces. Similar considerations also indicate that stable nuclei above a certain size will never occur, and, in fact, the uranium nucleus is the heaviest found in nature, and it is not completely stable, for in about five thousand million years half the uranium atoms in any lump transform themselves, through a series of changes, into lead. The heaviest stable atom is that of bismuth, with atomic number 83 as compared to 92 for uranium.

What has been said is, of course, the barest indication of the very complicated and difficult considerations on the basis of which experts have been able to calculate the energy required to produce fission in different nuclei and also the gain of energy that the addition of

a neutron represents, with the result that the conditions for fission of different nuclei have been predicted.

We will now consider some of the results of experiments on nuclear fission. The two heaviest atoms found in nature, uranium and thorium, can both be split by neutron bombardment. The very scarce element protoactinium, of about the same weight, is also subject to fission. In the case of thorium only fast neutrons—and by fast we mean possessing velocities of thousands of miles a second, velocities something like those of the alpha particles—are effective. In uranium, however, both fast and slow neutrons can produce fission. By slow neutrons we mean those whose velocity has been reduced by frequent collisions with light nuclei, say, until it is about the same as the velocity which hydrogen atoms have in virtue of the ordinary heat agitation, that is, a velocity of some hundreds of yards per second: they are the "thermal neutrons" mentioned in the last chapter.

The effect which a neutron has on a uranium atom depends on which particular isotope we consider. Natural uranium consists of three isotopes: one of mass 234, which is very scarce and constitutes only about 0·006 per cent. of the whole: one of mass 235, which is commoner, but still only makes up 0·7 per cent.: and the common isotope 238, which constitutes about 99·3 per cent. of uranium. The slow (thermal) neutrons produce fission in the isotope 235, but not in the common isotope 238. Fast neutrons can cause fission in 235, but are not as effective as the slow neutrons.

It is also important to note that neutrons of certain speed are captured readily by U-238, producing a new isotope U-239. This is unstable, and gives out a beta

particle, i.e. a swift electron. Now, the loss of one unit of negative charge is equivalent to the gain of one unit of positive charge, so that the atom formed has atomic number 93, in place of the 92 which characterizes uranium. The new atomic number means, of course, new chemical properties: an element hitherto unknown has been formed. The name Neptunium has been given to it: the symbol is written Np.

Neptunium, however, is not stable, and itself, in due course, gives out a beta particle, which means that an atom is formed which still has the same mass, 239, but has atomic number 94, and so represents another new element. This has been named Plutonium, written Pu[1]. The production of the new elements is represented in Fig. 14. Plutonium is of the greatest importance for making nuclear energy accessible. Thermal neutrons produce fission in it, as they do in U-235.

Recently Dr. G. T. Seaborg, co-discoverer of plutonium, announced the discovery of the elements of atomic numbers 95 and 96, which were obtained by bombarding U-238 and Pu-239 with helium ions of energy 40 million electron volts from the Berkeley cyclotron. The names Americium and Curium[2] (after the Curies) have been given to these new elements, about which little has so far been published. It is possible that soon elements of even higher atomic numbers will be made, naturally all unstable.

For the moment we will leave thorium out of the

[1] The names Neptunium and Plutonium are derived from those of the two outermost planets, Neptune, discovered in 1846, and Pluto, discovered in 1930. Uranium was named after Uranus, discovered by William Herschel in 1781, as the outermost of the planets known in his time. Plutonium might, however, well have been named directly from Pluto, the god of infernal regions.

[2] The names Pandemonium and Delirium has been suggested by a cynic for these new elements.

question, and consider the possibility of obtaining energy from uranium. The neutrons that are discharged by the nucleus when it splits issue with a very high energy, almost equivalent to that which would be

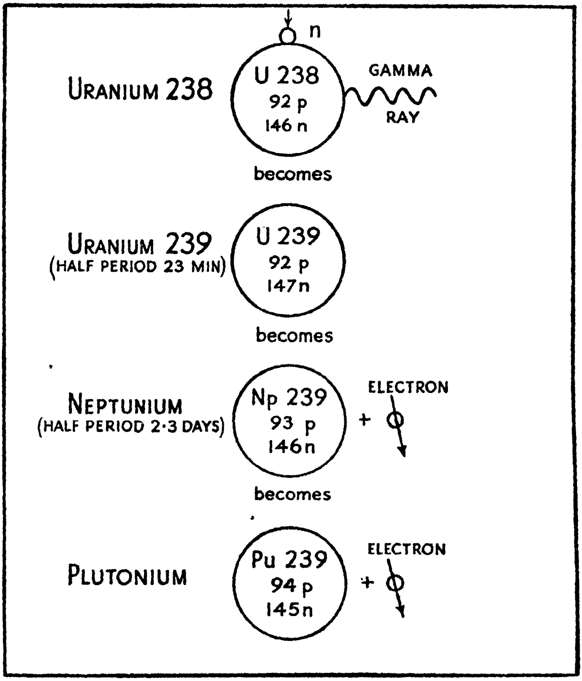


Fig 14. The growth of plutonium from uranium.

produced in a charged particle by a field of a hundred million volts. Therefore, to produce a chain reaction, we must have either a great concentration of atoms in which fission is produced by swift neutrons, or we must have some way of reducing, without capture, the speed of the neutrons. We have referred to the way in which the speed of neutrons can be reduced by collision with

hydrogen nuclei, but hydrogen, although most effective in stopping neutrons,[1] has the disadvantage that it can combine with neutrons, forming deuterium (heavy hydrogen), with the emission of a gamma ray. It therefore not only slows down the neutrons, but absorbs them. However, other light elements can be used to slow down neutrons, or to act as *moderators*, as they are called; that is, they can be used to moderate the energy of neutrons without absorption. The elements that have been chiefly considered in this connection are heavy hydrogen, often called deuterium; beryllium; and carbon. Helium is out of the question because it does not form chemical compounds, and in the gaseous form would take up too much room, and lithium and boron are unsuitable because they absorb neutrons. The fact that deuterium can be used as a moderator, together with the importance of moderators in nuclear reactions, explains why we were so anxious to destroy the stocks of heavy water which were in German hands in Norway during the war. It must be remembered that the substances used as moderators must be very pure: the large effect of quite small quantities of impurity in processes where collisions are in question has already been pointed out. Any foreign substances present to the extent of more than a few parts in a million may have serious consequences. Carbon is probably the moderator most extensively used nowadays, but it is carbon prepared to a degree of purity never found in commerce or even in ordinary laboratory operations. It is in the form known as graphite.

[1] Layers of water five feet thick or so, enclosed in tanks, are arranged round cyclotrons, in order to shield the workers from the neutrons generated when the cyclotron is working.

Considering first the case in which a moderator is not used, we know from what has been said that it is the 235 isotope of uranium that will be favourable for a chain reaction, for swift neutrons can produce fission in this nucleus. We must not have the uranium 238 isotope present to any appreciable extent, because the nucleus of that atom reduces the speed of swift neutrons by a particular kind of collision, and also captures neutrons of moderate speed without fission, but with the formation of neptunium. In order to produce this type of chain reaction, therefore, we need to separate out U-235 from the relatively plentiful U-238. With pure U-235 a neutron or two released by the chance impact of a cosmic ray particle should release swift neutrons from other atoms by fission, which in their turn would produce fission, so that there should be an instantaneous release of an enormous amount of nuclear energy—always supposing the lump of U-235 big enough. For if it is below a certain size we have shown that sufficient neutrons will escape harmlessly at the surface for the chain to be broken, just as a piece of wood in which the heat is escaping at above a certain rate will not burn if set on fire at one place. Two lumps of U-235, each harmless, should automatically disintegrate if brought together so as to form a bigger lump, supposing that the sizes are suitably chosen, for there are always a few neutrons about to start the show. This is, in fact, the way in which atomic bombs are detonated, and U-235 is the substance of which one type of atomic bomb is made.

This fast neutron reaction is ideal for an explosion, because in one set of conditions reaction does not go at all and in another set of conditions, easily produced,

it runs away with unlimited rapidity. In the same way dynamite is suitable for explosive release of energy, although the energy released when a pound of dynamite detonates is less than that produced by the burning of three ounces of good coal, but is very unsuitable as fuel, not only because the energy per pound is not very great, but also because it cannot be made to come out slowly.

Before we consider the U-235 problem any further, let us turn to the other possibility, involving the use of moderators and slow neutron reactions. If we have ordinary uranium, consisting almost entirely of U-238, we know that fast neutrons will not produce fission, but that neutrons of intermediate speed, such as will be produced in the course of the slowing down, will be strongly absorbed, producing U-239, while thermal neutrons will produce fission of the U-235 present in small proportions. The U-239 will practically all become plutonium within a matter of days, so that a quantity of uranium containing a suitable disposition of moderator will grow plutonium and at the same time, of course, will develop heat, since energy is released in the various nuclear transformations. The plutonium can afterwards be separated from the uranium by chemical processes, since, having a different atomic number, its chemical properties are different. Hence we have the possibilities of generating heat by nuclear methods and of growing plutonium. Plutonium itself behaves like U-235 in that it generates an instantaneous chain reaction if the lump is big enough and so is suitable for making atomic bombs.

Of course, for these possibilities to be of any use we must be able to govern the process, so that the generation of heat neither runs away and reduces the pile

to scrap, nor dies out. Low speed neutrons means that the reactions proceed comparatively slowly and that in its turn implies that we can control the rate. This control can be exercised by inserting and removing slabs or bars of a material that absorbs neutrons: if the reaction is going too fast they are put in, to be withdrawn if it shows signs of going too slowly. A suitable absorber of neutrons is the metal cadmium, or boron.

It should be mentioned that control is made much easier by the fact that a certain percentage of the neutrons emitted do not issue instantaneously when fission occurs, but after a short interval. These are the so-called "delayed neutrons": the delay is comparatively short, ranging from somewhere about a hundredth of a second to a minute or so. Advantage can be taken of this phenomenon in the case of both fast and slow neutron processes, but little has been published as to how the desired effect is produced.

An assembly of uranium, moderator and absorber, with suitable arrangements for cooling if the heat cannot be utilized industrially, is called a primary reactor (sometimes a nuclear reactor, sometimes simply a reactor) or "pile." In most of the piles that have been described the moderator used is very pure carbon, but heavy water is employed in at least one case. The uranium is in the form of rods embedded in the channels in the graphite moderator, from which they can be withdrawn. Cadmium or boron rods, attached to suitable instruments, act as controls. The cooling is carried out by water or air circulating in pipes of suitable material. This cooling, of course, represents a waste of heat which was tolerated as long

as the main object of the pile was to grow plutonium.

No doubt in the future the heat will be generated in such a way that it can be used for industrial purposes, in which case we shall have atomic fuel taking the place of coal and oil, which combustibles may be called molecular fuel. For whereas in the pile the heat is derived from reactions in which one kind of atom becomes another kind of atom, in an ordinary furnace the molecules of the fuel combine with the oxygen of their air to become new kinds of molecule. Thus the molecules of petroleum contain carbon and hydrogen, and, on burning, the carbon and hydrogen combine with oxygen to form molecules of carbon dioxide and of water.

A sketch of the lay-out of an atomic pile for industrial use[1] is shown in Fig. 15. The "atomic furnace" contains uranium rods, interspersed with rods of moderator and control rods, one of which is shown partly withdrawn. The boiler is shown as a coil of pipe containing water, heated by the very hot gases from the furnace which are circulated by a blower. The steam from the boiler is supplied to a turbine which drives the generator of current, the dynamo, as in an ordinary power station. The radioactive fission products are removed from the furnace by special means.

It must be remembered that in all the nuclear transmutations involved in the pile a small part of the energy set free appears as radiations. The fragments resulting from nuclear fission are themselves unstable, that is, they are artificially radioactive elements which

[1] This diagram was produced by the Clinton Laboratories, Oak Ridge, Tennessee and I am indebted for it to the Monsanto Chemical Company, which operates the laboratories on behalf of the U.S. Government.

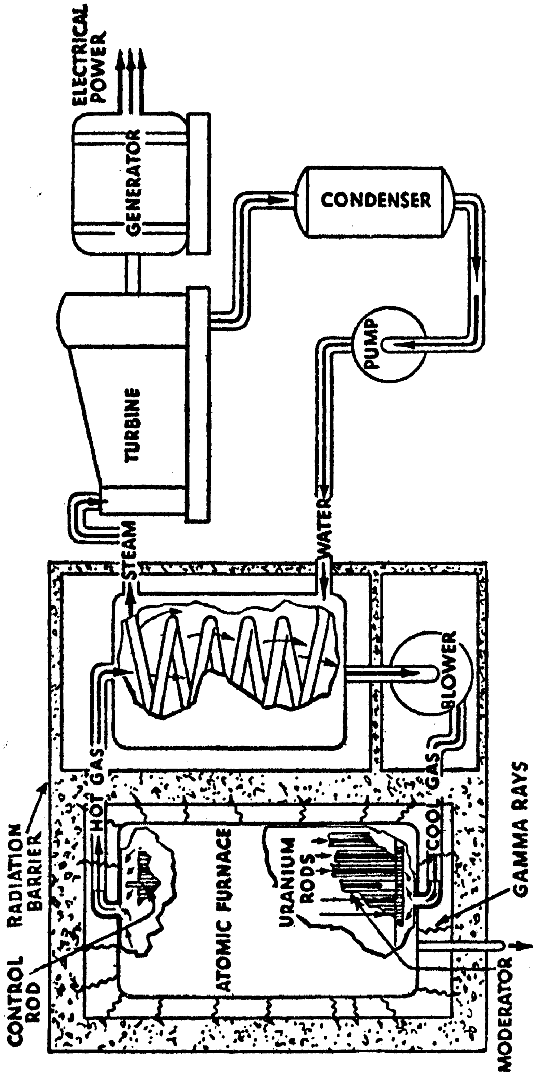


Fig. 15. General scheme of an atomic pile for industrial use.

give out swift electrons—beta rays—and gamma rays. The transmutations of U-238 into plutonium is also attended by heavy emission of beta rays and gamma rays. The beta rays are easily absorbed: the gamma rays, which are of the same type as X-rays, are very penetrating and very injurious to health, producing, among other injuries, grave effects on the spinal marrow and so ultimately on the blood corpuscles. The activity of a pile is enormous, and may be equivalent to that of thousands of grams of radium—and one gram of radium is considered an extremely dangerous entity, to be treated with great precaution. This means that nobody must come near the pile, so that all the operations, such as withdrawing and inserting the uranium slugs, and adjusting the cadmium and boron absorbents, have to be conducted by remote control.

The pile must be surrounded by walls, usually of concrete five foot thick or so, to absorb the gamma rays: the walls must also be airtight, so that air carrying the radioactive products cannot escape. The methods of distant control have been worked out, and the protecting walls are merely a matter of expense if we are considering the use of nuclear energy for large permanent installations, such as power stations for generating electricity. However, there has been a certain amount of glib talk of nuclear energy for driving aeroplanes, motor cars, railway trains and so on. The necessity of very heavy protecting walls for shielding the pilots and drivers make such projects quite impracticable. We cannot even hope for some new invention in the way of shielding material, for, roughly speaking, the shielding effect merely depends upon the mass of matter put in the path of the radiation. If we

could use platinum for shielding, the walls would be much thinner, but just as heavy.

Let us consider first the question of applying nuclear energy to the manufacture of bombs. We have seen that there are two possible materials in question, the 235 isotope of uranium and the new element plutonium.[1] In addition there is an isotope of uranium, U-233, which does not occur in nature, but can be formed from the element thorium in nuclear fires burning U-235. Very little has been published about it, and all that we shall say is that it requires uranium for its production, so that uranium is indispensable for any process leading to atomic bombs.

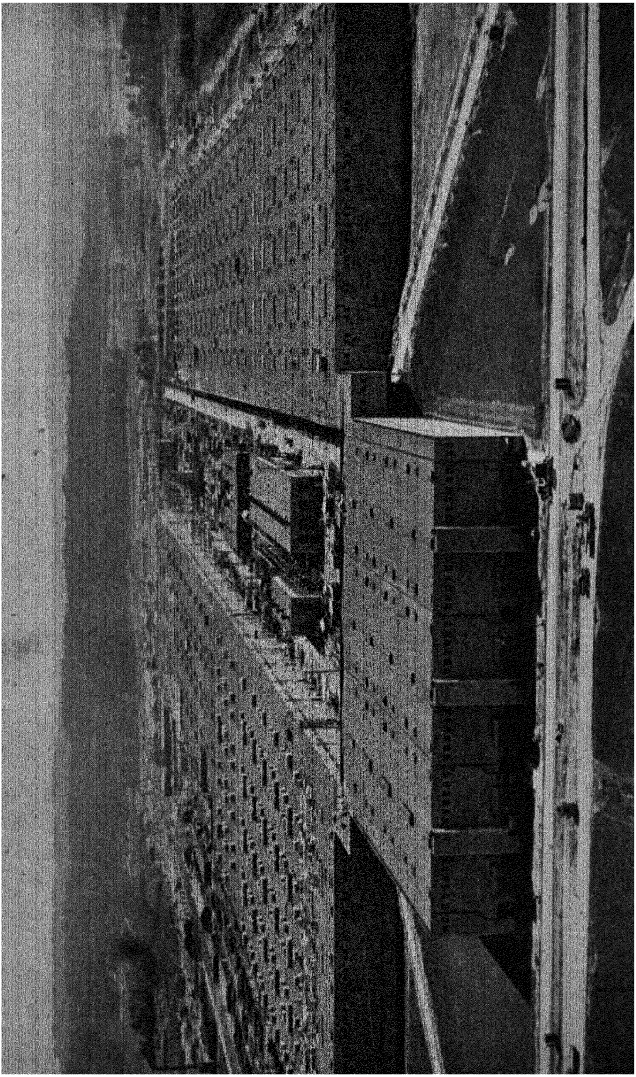
There are great difficulties in the way of producing both U-235 and plutonium. Since uranium can be mined by the hundreds of tons, there is plenty of U-235 available, although it constitutes less than one per cent. of the natural metal, but the separation of one isotope from another is an extraordinarily tedious process. The ordinary methods of separating two elements, say silver and lead, which are found intimately mixed in nature, depend upon utilizing the different chemical properties of the elements: the lead may be oxidized under conditions in which the silver is not attacked by oxygen, when the lead oxide floats on the surface and may be drawn off. But all isotopes of the same metal have, by definition, the same chemical properties, so that processes depending upon differences of physical properties associated with mass must be used, and these are all very slow. On the other hand plutonium, being a new chemical species,

[1] It was at first supposed that the manufactured plutonium was a completely new element, not found in nature, but recently it has been stated that minute amounts have been found to occur naturally.

PLATE XI

The destruction of the cities of the plain by fire from heaven, as painted by Lucas van Leyden (1494–1533).

PLATE XII



Diffusion plant of Clinton Works at Oak Ridge, Tennessee, set up in connection with the atom bomb project.

can be separated out from uranium by chemical means, difficult, it is true, but comparatively rapid. The disadvantageous feature here is that all the plutonium has to be artificially grown in a pile, and this is a slow process.

Isotope separation can be carried out in various ways, but the difficulties are so great that before the war quantities of individual isotopes which had been prepared were in the region of fractions of a milligram, that is, roughly speaking, a thirty-thousandth of an ounce. For atomic bomb purposes U-235 was required by the tens of pounds, probably by the hundredweight,[1] so that the scale was as completely different as is the pocket torch from the giant searchlight.

One method of separation is to make use of diffusion through a porous barrier, if the isotope mixture can be obtained in the form of a gas. In any mixture of gases the lighter molecules move faster than the heavier ones: thus in a mixture of hydrogen and oxygen the average speed of the hydrogen molecules is about four times that of the oxygen molecules. This is an extreme case: where the difference of mass is much smaller the difference of speed is much smaller. As a result of the difference of speed the lighter gas passes through a porous wall (of, say, unglazed "biscuit" china, or of plaster of Paris) quicker than does a heavier gas, so that of a mixture which has experienced diffusion the portion that has gone through the wall contains a greater proportion of the lighter constituent than normal, and the part that has not passed through contains a greater proportion of the heavier constituent.

[1] Professor Joliot-Curie is reported as saying that there were 136 pounds of U-235 in the uranium bombs.

The repetition of the diffusion process again and again can ultimately lead to a tolerably complete separation of the heavier and the lighter constituent.

A second method depends upon the fact that if a particle carrying a given charge is moving with a given speed in an electric or magnetic field, the amount by which it is swept aside from its path will be determined by the mass of the particles—light particles will be more deflected, heavy particles less. Reference was made to this effect in Chapter III, when the determination of the mass of the electron was being considered, and in Chapter V, when isotopes were being discussed. The amounts of isotope separated in the experiments there described, which established their existence, were unweighably small, and detected by their photographic effects, but clearly the scale of the experiment can be increased until weighable quantities are separated. Still other methods of isotope separation exist.

The diffusion and electromagnetic methods of separation have been used in the U.S.A., on a scale undreamt of before the war, to separate isotopes in quantity. For the diffusion methods the uranium must be prepared in the form of a gaseous compound; the compound used is that formed with fluorine, uranium hexafluoride, and it is to be noted that fluorine consists of one isotope only. It would clearly complicate matters if the mass of the fluorine itself were variable. The difference in mass between the hexafluoride of U-235 and U-238 is less than one per cent., and the separation factor, being proportional to the square root of the ratio of the molecular weights, is less than a half per cent., so that the separation of the two isotopes in one stage of diffusion is very small. At

each stage half the gas is allowed to diffuse through the porous barrier; the enriched half is then pumped away and taken to another stage of diffusion, when it is again slightly enriched, while the impoverished half is returned to the feed of the next lower stage. The whole cascade, as it is called, contains many complicated recycling stages. To give a notion of the size and complexity of the plant necessary if pounds of tolerably pure U-235 are to be obtained it need only be said that in order to obtain a specimen of U-235 that is 99 per cent. pure about four thousand stages of diffusion are necessary, and that the final sample of uranium 235 hexafluoride gas is about a hundred thousandth of the gas with which the first stage was started. It has been stated that the rate of production of U-235 was 400 grams (about 14 ounces) a day.

The total area covered by the gaseous diffusion plant of Clinton, shown in Plate XII, is some six hundred acres. Much special research was necessary to obtain a good material for the construction of the porous walls, for the holes have to be less than a millionth of an inch across. The pumps also presented many problems, and two new types of centrifugal blower were developed. The great isotope separation plant at Clinton, Tennessee, comprises both diffusion and electromagnetic installations. The electromagnetic separation is carried out according to the scheme of Fig. 7. The large scale installations require, of course, giant magnets, whose poles are some feet in diameter. The great magnet used in the first large scale magnetic separator was obtained by dismantling the 37 inch cycloton at Berkeley, California, where Lawrence's laboratory is situated. The consequence

is that the magnetic separators are called calutrons, which is an abbreviation of California University Cyclotron. The calutron plant itself covers five hundred acres at Clinton.

The cost of this enormous project of isotope separation was announced in 1945 to have been over one thousand one hundred million dollars (£275 million, at the official rate of exchange), and that of the plutonium project as about three hundred and eighty-four million dollars (£96 million), so that either method of obtaining pure fissionable material is extremely expensive, even supposing that experience has enabled the operators to effect considerable economies.

The U-235 and the plutonium were prepared originally for the purpose of making atomic bombs, and Dr. Seaborg, whose name has been mentioned in connection with the discovery of plutonium, americium and curium, has announced that plutonium was the basis of the atomic bomb that devastated Nagasaki. The Hiroshima bomb was of U-235. The quantity of fissionable material used in a bomb is still secret, but it is known that it must lie between about four pounds and two hundred pounds. The degree of purity obtained is also secret at the time of writing.

The general principles on which the bomb is constructed are, however, known. The problem is to bring two pieces of fissionable material, each of which is too small to go off by itself, as already explained, together so as to form a lump above the critical size, that is, a lump in which the number of neutrons affecting fission is greater than the number escaping or suffering non-fission capture. The pieces must also be brought together very rapidly, because otherwise

large bits of the material might be blown away before the chain reaction had been started in them, and so be wasted. Further, the number of stray neutrons, which might set off one half before the other half, must be kept as low as possible. It is probable that the "safe"

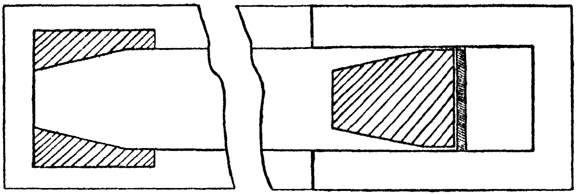


Fig. 16. Scheme for rapid production of a piece of fissionable material of explosive size. The fissionable material is shown shaded, and a "safe" lump is shot into contact with two other "safe" lumps.

pieces are shot together by some sort of gun mechanism so as to constitute as rapidly as possible an explosive mass. It has been suggested that two "safe" pieces are arranged at a small distance apart, as shown on the left in the diagram (Fig. 16), and that, when the bomb's trigger is released by the timing mechanism, a third "safe" piece, shown on the right, is shot from some sort of gun so as to arrive between them and constitute a chain-reacting mass, which releases the greater part of its energy before the bomb can be dissipated as unexploded bits. The actual construction of the bomb is a great technical problem.

It should be made clear, perhaps, that the effects of the atomic bomb are due to three distinct causes, blast, heat radiation, and radioactivity. The result of the fission is that the two parts into which the nucleus splits are thrown apart with enormous energy of motion.

This energy of motion is, by various collisions, communicated to the surrounding air, which in consequence rises almost instantaneously to an extremely high temperature. The increase of temperature means that the body of glowing hot air thus suddenly established simultaneously reaches an enormous pressure and then promptly expands, producing a blast which moves outwards as a wall of pressure. This is followed by a wave of low pressure, or suction. The crest of high pressure followed by a long trough of low pressure is a feature of the blast from ordinary explosions, and many of the queer effects observed with high explosive bombs dropped from aircraft were due to the wave of suction. With the atomic bomb, however, the high pressure wave in general lasted long enough to push over buildings before the low pressure came into action, so that the experts in assessing destruction were able to note many features distinguishing the type of blast damage in the Japanese cities from that in London, say.

The heat radiation is an effect not observed with ordinary high explosive bombs, since with them the temperature never becomes sufficiently high. It is not direct flame from the bomb, but a kind of super sunshine—infra-red, visible and ultra-violet radiation so intense that, although it lasts only a second or so, it produces pronounced heat and chemical action[1] in any body on which it falls. The surface scorching due to the heat radiation has been called *flashburn*. It is characterized by some very queer effects; for instance,

[1] What is ordinarily called "sunburn" is produced, not by the heat of the sun, but by the ultra-violet radiation (see, e.g., E. N. da C. Andrade, *The Mechanism of Nature*). I have not seen any analysis of the type of burn produced by the atomic bomb.

while it produced severe burns on exposed skins at distances well over a mile from the centre of explosion, even light clothing afforded protection from it, since the duration of the flash is so short. Any kind of wall, of course, affords complete protection from the momentary effects. The heat radiation can, however, cause fires when it falls on inflammable material.

The radioactive effects are due partly to the intense penetrating radiation, of the gamma ray type, which is released when the nuclear fission takes place; partly to the products of the fission, which are themselves radioactive; and partly to ordinary materials made radioactive by bombardment with neutrons released in the nuclear disintegrations. The direct effect of the neutrons on human beings has also to be taken into account. The effect of the radioactive products, with the bomb bursting at a fair height, was unimportant, as far as can be made out. Contrary to widespread reports, the radioactivity in the ruins, even soon after the explosion, was trifling, and plant life flourished in both cities.

The serious effects were due to the gamma radiation, which is, of course, a very different agent from the heat radiation just discussed. The wavelength is something like a millionth of that of the heat radiation, and it can traverse great thicknesses of solid wall and produce devastating, although not immediate, results. The rays attack the bone marrow, to which they easily penetrate, and this ultimately causes grave effects in the blood, which in severe cases, lead to death in a matter of weeks. This is not a suitable place for a description of the distressing symptoms of the injuries produced by intense gamma radiations, which are just

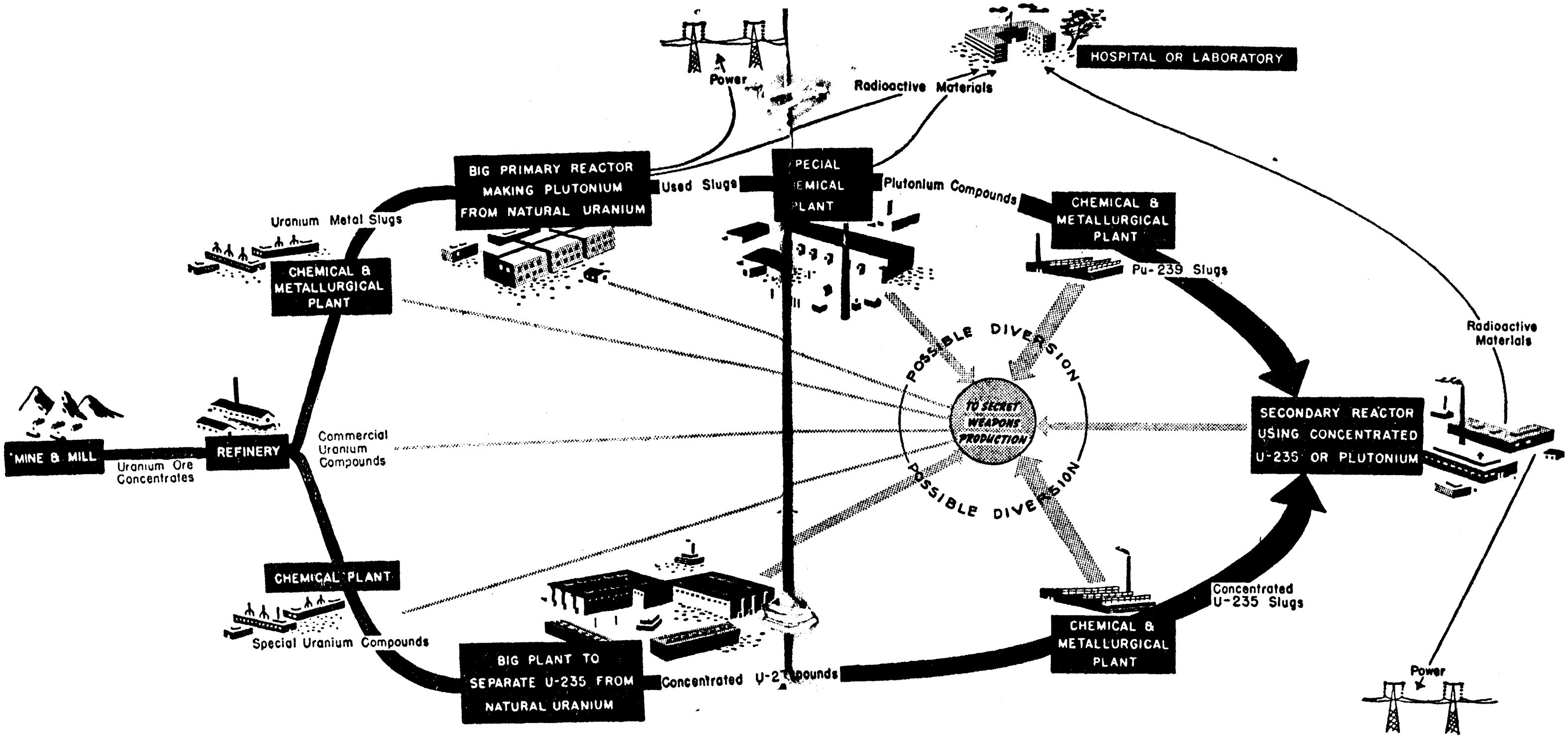


Fig. 17. Pictorial chart showing the processes through which uranium passes from the mine to the final production of atomic energy for peaceful purposes. The possible stages at which material could be diverted for the secret production of bombs are indicated. (Waste products from the various stages in the processes may be treated to recover the uranium or plutonium which they contain. For simplicity, such operations have not been shown.)

what the workers in nuclear energy installations have to be guarded against.

The way in which the Japanese cities of Hiroshima and Nagasaki were destroyed, each by a single bomb, has been graphically described in a Government report.[1] "The scale of the disaster brought city life

and industry virtually to a standstill." Light concrete buildings collapsed at a mile from the centre of bomb damage. It is often supposed by the layman that the amount of energy released by the bomb was stupendous,

[1] *The Effect of the Atomic Bombs at Hiroshima and Nagasaki.* H.M. Stationery Office. 1946.

but this is not so. It was officially announced at the time of the Hiroshima attack that the explosive energy of the bomb was equivalent to that of twenty thousand tons of T.N.T. Since the explosive effects produced by the blast from an atomic bomb and by that from an ordinary explosive differ somewhat in nature, and since no one quite knows what such an enormous mass of T.N.T. would do, this estimate must be taken as very rough, but it will serve. The actual energy released by a pound of T.N.T. exploding is about an eighth of that released by the burning of a pound of coal, so that we can say that the energy of, say, the Hiroshima bomb was equivalent to that from two thousand five hundred tons of coal,[1] a very different figure from that often put forward by railway carriage experts, if I may so term the casual conversationalists always ready to proffer information on matters rather beyond the scope of their knowledge. The reason for the terrible destruction is not so much the amount of energy as the rapidity with which it is released. If the total energy of motion of the air moving in our streets in the course of a day, at a time of light winds, were to be suddenly communicated to the air in a second or less the consequent super hurricane would blow down all ordinary houses. The tremendous advantage that atomic energy has for destructive purposes is not that it is a cheap source of energy—so far, it is a very expensive one—but that the energy is concentrated in a very small mass and can be released very suddenly. For explosives, rate of supply of energy is everything.

[1] This is about the amount of coal required to supply a city of a million inhabitants with electric power and light for a day.

The reader may be interested in seeing the anticipation of an atomic bomb which Lucas van Leyden, a Dutch artist, painted more than four hundred years ago. The picture "Lot's daughters," of which Plate XI shows the main part, represents the destruction of the "cities of the plain." In the air is seen a burst which is raining down destruction, and, below, the sinking ships, the falling towers and other signs of the destruction caused by the celestial portent. The resemblance to the modern catastrophe is striking.

Let us now turn to the possible ways in which we can take advantage of atomic energy for peaceful purposes. They can be roughly grouped as industrial uses; research uses, physical, chemical and biological; and medical uses. The obvious industrial use is to turn the heat generated in nuclear reactions to some of the purposes for which large coal or oil burning furnaces are used at the present time. We are never likely to be able to use nuclear energy for driving aeroplanes, automobiles or locomotives of the present size because, as has been pointed out, the release of nuclear energy is inseparably bound up with penetrating radiations that have deadly effects, so that very heavy walls are necessary to protect the operators. It is just possible that in the future large ships, or even very large aeroplanes, may be able to economize sufficiently on weight of fuel to carry these protecting walls, but before that we are almost certain to see nuclear energy turned to some such purpose as generating electricity on a large scale. The atomic furnace "burns" nuclear fuel, in general uranium, and the products of fission, atoms such as barium, represent the ash. The heat generated, which is regulated by rods of cadmium or

boron, in the way already described, has to be turned to generating steam or some other agent by which mechanical power can be produced. This is by no means as easy as it may sound at first. In the case of the pile, the water must be kept from direct contact with the uranium, which it would corrode, and with the graphite: the tubes which contain the water absorb neutrons, which tends to disturb the working of the pile. Spaces are required not only for the regulating rods but also for the various instruments which indicate the temperature, the intensity of the radiations and so on. It is clear that the design of a nuclear furnace for large-scale heat production is a very complicated matter, and that, if it requires great skill and experience to design a large coal-burning boiler installation, it will require even more to contrive a successful uranium outfit which shall produce steam economically.

The possibility of the project has been established. When controlled methods of generating nuclear energy have been further developed, the economic factors must in the end decide to what extent nuclear energy will be used for industrial ends. This economic question is clearly also a most complicated matter, involving the relative cost of obtaining and transporting the raw materials and of producing steam, say, with them. Once the steam has been produced, the generation and transmission of electricity can be the same in both cases. One plan, which we may consider briefly, is to produce fissionable material, say plutonium, which can be made to produce energy in a non-explosive way in a suitable controlled outfit. In the case of coal the cost is that of mining; in the case of oil that of boring, pumping and purifying; in both cases

there are heavy transport expenses. In the case of plutonium, we have to mine and transport the uranium, but the quantities needed are comparatively small, so that this is probably a relatively minor item. We have to grow the nuclear fuel in a pile: the heat generated here in the process of producing the plutonium is one item to be set to the credit side. To the debit side are the costs of running the pile, with its skilled personnel, and its need for replacements. The separation of the plutonium and its admixture with suitable controlling material are also debit items. If pure plutonium is required for military purposes, or for industrial explosives—for there may be a possibility of using nuclear explosives for demolitions, like the Hell Gate[1] undertaking—it will be represented by a price depending on the demand. In the case of coal and oil the very valuable by-products, on which large chemical industries are founded, must be taken into account. In the case of the pile there are, too, valuable by-products in the shape of artificially radioactive elements and powerful sources of radiation. All these points merely indicate how very complex the question is.

[1] The passage between New York Harbour and Long Island Sound was obstructed by a number of rocky reefs, which led to frequent wrecks, in consequence of which the name Hell Gate was given to the locality. After earlier work on a lesser scale on other reefs, a great operation to break up Middle Reef rock by explosive was carried out in 1885. Over forty thousand cartridges containing about twenty tons of dynamite, in addition to over one hundred tons of an explosive called "rackarock" (seventy-nine parts of potassium chlorate and twenty-one parts of dinitrobenzene), were used, and about three hundred and fifty thousand cubic yards of rock were broken up. One advantage of nuclear explosive for demolition would be that an amount equivalent to thousands of tons of ordinary explosive could be put into one small bore hole, some inches in diameter, but whether the local concentration of explosive force can be used to advantage is a matter for the civil engineers. The trouble is that of the limiting size, which prevents smaller charges being used.

There is, however, one clear point in which nuclear fuel has the great advantage. Its weight, for a given amount of energy production, is negligible when compared to the weight of coal or oil, so that transport costs are trifling. This indicates that the case in which atomic power is likely to be economically most advantageous, at any rate in the early stages, is where the question arises of generating power at a place remote from all natural supplies of fuel in the shape of coal or oil and remote from natural water power, say in the Sahara desert. In the atomic case the yearly supplies of fuel, instead of requiring hundreds of trains, can probably be carried in a few lorries. This is not to suggest that the Sahara will in the future be the only place where nuclear energy will be utilized for industrial purposes: there are obviously great possibilities in the United Kingdom, where the coal problem is so grave.

Before predicting universal prosperity as a possible result of the peaceful application of nuclear energy, the optimist should remember that the fuel cost is a comparatively small part of the expense of generating electricity, probably somewhere about 15 or 20 per cent. Professor Marschak has calculated that if all coal and oil used in stationary power plants were replaced by fuel which cost nothing, the nation's working week would be reduced by 45 minutes, so that the limitless leisure foretold by some enthusiasts must find its source in some other development than nuclear furnaces.

For the advancement of scientific knowledge the pile and its products will be of the greatest value. For example, as we have seen, the radiations in the pile

produce from thorium a new isotope of uranium, U-233, which is the parent member of a whole new series of radioactive elements, to be added to the three series known to Rutherford—the uranium, the thorium, and the actinium series. The new artificially manufactured uranium isotope changes into a new isotope of radium and so on, until we finally get the stable element bismuth, when the changes stop, just as with the radioactive series hitherto known we finally get the stable element lead. This new series is of the utmost interest to the physicist and it is quite possible that other series will soon be discovered.

The scale on which radioactive effects can now be produced is quite new in the history of science. Cockroft tells us that the rays from a moderate pile equal in intensity those from several million of the most powerful radium sources used in medicine. This gives us, for instance, the opportunity of preparing on a large scale new elements, particularly radioactive isotopes of known atomic species. These are of great value for research purposes. For example, the diffusion of certain atoms of a solid or liquid through the other atoms of the same kind can be followed if some of the atoms are artificially radioactive, although the chemical behaviour of all the atoms present is the same. This diffusion is of great interest to physicists. They can also be used as tracer elements in biology, along the lines already indicated. In general, the intense source of neutrons and of gamma rays constituted by the pile give us an opportunity for effecting nuclear reactions—for studying what may be called nuclear chemistry—on a large scale. It is as if in chemistry up to a certain date the quantities of ordinary reagents,

acids and alkalis, that had been available were microscopic, so that all reactions had had to be carried out with minute drops, and suddenly bulk quantities in quart bottles were produced, together with large burners and furnaces in place of candle flames. There is now under construction a Canadian pile at Chalk River which will exceed in activity anything that has so far existed. With it new elements heavier than the curium and americium already mentioned may be produced. The products of the fission of the uranium nucleus can also be studied with gram-weight quantities. Further, the behaviour of the neutron, which may itself be unstable under certain conditions, and break up into a proton and an electron, say, can be studied with intense sources. In nearly every research laboratory there will be an eager demand for artificially radioactive elements, as soon as the Guardians of the Piles make them available.

Apart from the research uses in medicine, such as those afforded by tracer elements, some hopes have been held out that the products of atomic energy may be used for curative purposes. There seem to be no indications so far that the neutron or gamma radiations can be employed for beneficial ends in this field, but the radioactive isotopes have been suggested for the treatment of disease. So far, apparently, only those of iodine and phosphorus have been employed. Iodine in the blood is picked up selectively by the thyroid gland, and it has been established that with radioactive iodine suitably administered a disease characterized by overactivity of the thyroid gland can be checked. Attempts have been made to treat cancer of the thyroid with radioiodine, but the results do not

seem to be conclusive. At any rate Dr. C. P. Rhoads,[1] writing on the subject, says "I personally cannot feel hopeful that we will have by radioactive iodine, straight inorganic iodine, an attack on a very large percentage of thyroid cancers." Radiophosphorous has been tried on certain other forms of cancer, with very moderate success, but it appears that there is a non-cancerous disorder of blood-forming tissue for which it is of use. The general picture is that nothing at all sensational has so far resulted from treatment with artificial radioactive elements. Dr. Rhoads, just quoted, after giving a very cautious account of what has been done so far, says "I am very hopeful—that startling discoveries will be made in the years to come —not next year or the year after, but in five, ten or fifteen years." A warning is sounded by Dr. Hermann Lisco,[2] who says: "One wonders whether unpleasant surprises are not in store for us if therapy with radioactive isotopes is to be attempted on a large scale before the toxicity of these substances has been carefully investigated." It is difficult for one who is not a medical man to pronounce on the subject, and I have therefore quoted two American doctors who have had the opportunity of studying the matter closely. There is not the slightest doubt as to the deadliness of the radiations, for quite apart from Hiroshima, where about five per cent. of the casualties were due to irradiation, there have been deaths due to accidental exposure among the scientific workers at the Los Alamos laboratories and elsewhere. Likening the

[1] Director of the Sloan-Kettering Institute for Cancer Research, U.S.A.

[2] Of the Harvard Medical School, at one time (possibly now) a member of the Health and Biology Division of the Argonne Laboratory.

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atomic weapon to a knife, its ability to inflict wounds and death is clear: whether it can be applied, like the surgeon's knife, beneficially, remains to be seen.

Somewhere about 1903 Rutherford said jokingly "some fool in a laboratory might blow up the world unawares."[1] To-day we are in the presence of a power which, if it does not threaten to disintegrate the material framework of our world, "the great globe itself,"[2] does foreshadow the possibility of the destruction of millions of men and of all our great cities, of the end of civilization as we know it, a situation crisply summarized by Professor Harold Urey's dictum "the next war will be fought with atom bombs and the one after that with spears." We have seen what the earliest atomic bombs could do: we can imagine with horror the possibilities when very long distance guided rockets have been developed from the beginnings exemplified in the German weapon, V2, each rocket carrying an "improved" atomic bomb. There is clearly no effective way of defending a surface city against such attack. The victor in an atomic war carried out years hence would be the country which retained sufficient rudiments of healthy population, of buildings and of tribal spirit to be able to act as a nation or as a community. How the danger of atomic

[1] On July 26th, 1903, Sir William Dampier wrote to Rutherford about "your playful suggestion that, could a proper detonator be found, it was just conceivable that a wave of atomic disintegration might be started through matter, which would indeed make this old world vanish in smoke." See A. S. Eve, *Rutherford.* 1939.

[2] "And, like the baseless fabric of this vision
The cloud-capp'd towers, the gorgeous palaces,
The solemn temples, the great globe itself,
Yea, all which it inherits, shall dissolve,
And, like this insubstantial pageant faded,
Leave not a rack behind."

Tempest, IV, 1.

conflict can be averted is the concern of every intelligent man and woman.

The matter has been considered in many quarters. In January, 1946, the United Nations Organization set up a Commission to deal with problems raised by the discovery of atomic energy, and this Commission established a Scientific and Technical Committee under the chairmanship of Professor H. A. Kramers, Professor of Theoretical Physics at Leyden in Holland. The Committee prepared a first report on the Control of Atomic Energy which appeared towards the end of 1946. This brief document lays down certain fundamental considerations, and contains an excellent diagram illustrating the processes through which uranium passes to produce atomic energy, which I reproduce in Fig. 17 (pages 172–173) by permission of the United Nations Department of Public Information. It does not, however, record any conclusion as to a machinery of control, which may be reserved for a later publication.

A much more detailed report, which produces a carefully considered scheme for control, has been issued by the U.S.A. Secretary of State's Committee on Atomic Energy, for whom it was prepared by a very distinguished and expert Board of Consultants. The Chairman was David Lilienthal, who as Chairman of the Tennessee Valley Authority had been responsible for one of the most prodigious engineering achievements of our times, and the members were Chester Barnard, President of the New Jersey Bell Telephone Company; Robert Oppenheimer, of the California Institute of Technology and the University of California, an atomic physicist well known for his work on artificial transmutations, and director of the laboratory

at Los Alamos,[1] in New Mexico, where the first atomic bomb developments and tests were carried out; C. A. Thomas, Technical Director of the Monsanto Chemical Company, which worked on important problems connected with the Los Alamos developments; and H. A. Winne, Vice-President in charge of Engineering Policy of the General Electric Company, which has been prominently concerned in the electromagnetic separation of isotopes. It will therefore be seen that all members were technical men accustomed to direct great projects, that they had all been prominently concerned with atomic development, and further—which anyone who has done much service on committees will appreciate—that the committee was a small one, consisting of only five men all told. The addition of another fifteen or twenty members to represent various government departments, professional bodies and so on, might have delayed and obstructed the work so seriously that we might still be awaiting a report.

The consultants state that whereas at the outset of their task they were far from confident, and considered that at best they could only indicate various alternative possibilities, they became more hopeful as they proceeded with their examination of the problems, and, concluding their work in a sanguine spirit, felt able to put forward definite recommendations as to a feasible plan of control. Most schemes previously put forward had assumed that all nations should be free to carry out atomic research and developments on any lines that seemed good to them, and that control should reside in an international inspection system with

[1] To-day probably the best-equipped physics laboratory in the world.

police organization and powers, whose function it would be to see that any large-scale developments did not trend in the direction of atomic weapons. On any such scheme it is intentions rather than acts that are illegal. It is characteristic of the consultants' scheme (as I propose to call it for convenience) that it rejects any purely police organization of this kind as impracticable and certain to lead at once to international jealousy, resentment and friction in general. As realists—I do not use the word as a contrast to idealists, for I hold that a man may have high ideals and still resolutely contemplate the actual results that any particular action is likely to bring in its train—they further consider the practical difficulties of putting any police scheme into execution, devoting attention to, in particular, the human factors. The inspecting staff would have to be numerous and expert, expert not only in science but in language and procedure. The task before them—the "immense and dreary task," as the report calls it—which would involve unwelcome intrusion; spying, or something very near it; and endeavour to unearth evidence of bad faith, is such that the very type of man required would be the least likely to consent to act. As regards numbers, the consultants state that for a large-scale diffusion plant about three hundred inspectors would be required to offer any real hope of guarding against diversion of the precious isotope. It is only necessary to consider in a spirit of reality the problem of inspection in a large and sensitive country by a corps of "foreign" inspectors to realize that the only conditions under which it could work would be those that would render it unnecessary.

The consultants' scheme of control is founded upon

the classification of certain definite acts as illegal, which is [illegible]y a much sounder basis than classifying intentions as illegal. They propose to divide all nuclear activities into two classes, dangerous and safe. Dangerous activities are those which can lead directly to the manufacture of atomic weapons; safe activities are those using small quantities of fissionable material for research purposes or those that make use of material which, although suitable for generating energy at industrial rates, is unsuitable for explosive purposes.

Here it is essential to refer to what is known as denatured material. Uranium 235 and plutonium are said to be denatured when they are mixed with some inert substance which slows up the reaction sufficiently to render it useless for warlike purposes. These denaturing substances must, if they are to be any use as a precaution, be very difficult to remove; that is, they must be isotopes of the fissionable material in question. To remove them, if suitably chosen and prepared, requires great plants of the kind erected at Clinton, although, perhaps, not quite of the same magnitude. Denaturing fissionable material does not mean, then, that it is made definitely unusable for warlike operations, but it does mean that it cannot be used unless both time and great isotope separation plants are available. It is, as we shall see, a valuable adjunct in control, but denatured material is not definitely "safe" under all conditions.

Under the consultants' scheme all dangerous activities will be assigned to an international organization, for which the name Atomic Development Authority is suggested. No doubt it will be called A.D.A. Prominent among dangerous activities are the mining and refining

of uranium and thorium, which are essential, as far as can be seen at present, for any atomic weapons—and even thorium cannot be used without uranium. Other eminently dangerous activities are the isolation of U-235, which, as we have seen, is a very heavy undertaking, and the growth of plutonium. Research on the large scale explosive nuclear reaction must further be classed as dangerous. The A.D.A. will have to control the world supply of raw material; to prepare fissionable material; to carry out research that will ensure that, as a body, it is at least as advanced in knowledge of nuclear matters as any individual nation. The tasks which have been indicated are not repressive, but constructive and positive, and, in consequence, interesting. It therefore seems likely that first-class men will be willing to carry them out in a spirit of active scientific co-operation. It would further be the task of the Authority to set up and control a system of inspection designed to see that certain dangerous acts are not being carried out nationally. These acts, such as the separation of U-235, fortunately require very extensive plant and are hard to keep secret. The existence of such a plant, and not its purpose, will be illegal under the scheme. No doubt the Authority will have to keep the boundary between dangerous and safe operations under constant review.

Under the scheme every nation would be free to engage in safe activities, under which heading clearly fall all researches using artificial radioactive elements as tracers in physical, chemical, physiological, technical and other problems. The quantities here involved are comparatively small and would require correspondingly small supplies of primary raw material. Such

researches are likely to be of great importance, so much so that Seaborg has stated: "It is not at all out of the question that the greatest gain to humanity from the atomic energy development will result from the widespread use of tracers to solve a multitude of problems rather than from the harnessing of the power itself."

The small nuclear reactors, or piles, that make radioactive isotopes will also act as sources of neutrons and gamma rays immensely stronger than any available before the coming of nuclear fission plants. The study of the effects produced by these radiations is also a safe activity.

The national production of power on a large scale—say from a hundred thousand to a million horsepower—from nuclear reactions is clearly a more difficult matter to keep within the undoubtedly safe category. However, a safeguard would be afforded by insisting that denatured fissionable material should be used in the reactors. It has already been pointed out that to remove the inactive isotope from the denatured material is a slow and elaborate process, so that no very stringent system of inspection would be necessary to detect it or to track the manufacture of atomic weapons for which the illegal process would presumably be undertaken. Under the scheme no uranium or thorium would be available, whose incorporations in the pile would produce further fissionable material. The energy produced by the consumption of denatured fissionable material must be distinguished from the energy produced in the pile where the plutonium, for instance, is being grown. Such piles will, of course, be in charge of the A.D.A. and the energy will be available for prescribed purposes.

The A.D.A. will, then, issue licences and supply materials for safe activities, and the conditions of supply will make it difficult to use the materials for the manufacture of atomic weapons. The licences will apply to the operation of particular types of reactor only. The A.D.A. will clearly have to exercise some inspection of the plants which it licenses, especially those used for power production, but this inspection will be concerned with technical and industrial facts and not with intentions, and can, it is hoped, be carried out with little friction by men whose scientific and technical knowledge has earned them international respect. The whole scheme, however, is designed to make a minimum of interference necessary, and to render service under the A.D.A. consistent with the maintenance of self-respect. Great stress is laid upon attracting the right type of personnel.

Any number of difficulties can, of course, be raised, but to many of us the Report on the International Control of Atomic Energy seems to afford a sound and practicable foundation. The consultants, men of parts and of long practical experience in science, pure and applied, and in the affairs of the world, tell us that, starting without preconceived views, they gained in the end a confidence that a rational and workable control was possible on the lines indicated. This is a message of hope for humanity.

Astonishing indeed are the changes that have taken place in atomic science in the past fifty years. In the early nineties of the past century the view generally taken was one that had been forcibly expressed by Clerk Maxwell some twenty years earlier. Following J. F. D. Herschel, he had called atoms "manufactured

articles" because, in his opinion, every atom of a given species was exactly like every other atom of that species, and had written: "The formation of an atom[1] is therefore an event not belonging to that order of nature under which we live. It is an operation of a kind which is not, so far as we are aware, going on on earth or in the sun or the stars either now or since these bodies began to be formed. It must be referred to the epoch, not of the formation of the earth or the solar system, but of the establishment of the existing order of nature, and till not only these worlds and systems, but the very order of nature itself is dissolved, we have no reason to expect the occurrence of any operation of a similar kind. In the present state of science, therefore, we have strong reasons for believing that in an atom we have something which has existed either from eternity or at least from times anterior to the existing order of nature." Clerk Maxwell was a towering genius who is universally acknowledged as one of the great innovators in physics, in many respects ahead of his times, but in the passage quoted every sentence, every phrase is in flat contradiction to fact as now established. If atoms are manufactured articles, then it is in the sense that we can set up factories to make quantities of very many kinds of new atoms at will. The manufacture of more complex atoms from the simplest kind of atom is going on now in the sun and stars and has been going on ever since these bodies were formed.

We are in the midst of the greatest revolution of scientific thought since Newton, but whereas Newton's

[1] Clerk Maxwell used the "molecule," but I have ventured to change it to "atom" because, as stated earlier, he often used the word to indicate what we now mean by the atom and this is clearly what he had in mind when writing the passage quoted.

discoveries had only an indirect and distant bearing on the material life of his age, the atomic discoveries have a straight and immediate influence on the life, and the chances of life, of each of us. The few leaders who have brought about the revolution and have put at our disposal a mastery of the material world undreamt of in the philosophy of the nineteenth century are intellects worthy to be compared to Newton. They and their collaborators are figures who are honoured in all nations and their achievements command the respect of competent thinkers everywhere. Unfortunately, our age, while great in intellect, is small in compassion. It has not produced a moral code that commands assent and obedience in the hearts of the rulers of the world, or political leaders who can speak to the nations in terms that command universal respect. We can probably hope no higher than that the instinct of self-preservation will find some such expression as the scheme of control that has been outlined. The caveman has the torch, and he lives not in a cave, but in a wooden hut in a dry forest. Even if he is not comprehending we may hope that he will be careful.

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